

On the interplay of response selection and visual attention
in dual-task situations –
a behavioral and electrophysiological investigation

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von Christina Brigitte Reimer, M.Sc.

Präsidentin der Humboldt-Universität zu Berlin: Prof. Dr.-Ing. Dr. Sabine
Kunst

Dekan der Lebenswissenschaftlichen Fakultät: Prof. Dr. Bernhard Grimm

Gutachter: 1. Prof. Dr. Torsten Schubert

2. Prof. Dr. Tilo Strobach

3. Prof. Dr. Rico Fischer

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Abstract

Response selection and visual attention are limited in capacity. Concerning dual-tasks of the Psychological Refractory Period (PRP) paradigm, it is assumed that response selection of Task 1 and Task 2 are processed sequentially. On the other hand, concerning conjunction search, it is assumed that visual attention selects the items and binds the item features resulting in a serial search process. In the present dissertation I investigated whether visual attention (i.e., feature binding) is subject to the same bottleneck mechanism as response selection in dual-tasks. Sequential processing of response selection and visual attention would provide evidence that both processes rely on a common capacity limitation, whereas concurrent processing would provide evidence that they rely on distinct capacity limitations.

Reaction time (RT) measures based on the locus-of-slack method, target detectability measures based on d' , and the event-related potential (ERP) technique to measure the N2pc (N2 posterior contralateral) were combined to investigate this question. Analyses focused on visual attention deployment in a conjunction search task, which was implemented as Task 2 in dual-task situations. Task 1 was a choice discrimination task. Both tasks were presented at variable temporal overlap (Stimulus Onset Asynchrony, SOA). The behavioral and N2pc results showed that response selection in Task 1 and visual attention (i.e., feature binding) in Task 2 operated concurrently irrespective of the stimulus modality in Task 1, the response selection difficulty in Task 1 and the type of presentation of the search display in Task 2. Based on a method that was developed in the present dissertation, it was possible to calculate how many items of the search display were processed in parallel to response selection. The results supported the conclusion that response selection and visual attention rely on distinct capacity limitations.

Keywords: visual attention, visual search, central bottleneck, Psychological Refractory Period (PRP) paradigm, locus-of-slack method, event-related potentials (ERPs), N2pc

Zusammenfassung

Die Reaktionsauswahl und die visuelle Aufmerksamkeit sind kapazitätslimitiert. In Doppelaufgaben des Paradigmas der Psychologischen Refraktärperiode (PRP) wird angenommen, dass die Reaktionsauswahlstufen in Aufgabe 1 und Aufgabe 2 sequentiell verarbeitet werden. Für Konjunktionssuchaufgaben wird angenommen, dass die visuelle Aufmerksamkeit Objekte selektiert und Objektmerkmale zusammen bindet, was zu einem seriellen Suchprozess führt. In der vorliegenden Dissertation wurde untersucht, ob die visuelle Aufmerksamkeit (d.h. Merkmalsbindung) demselben zentralen Verarbeitungsengpass wie die Reaktionsauswahl in Doppelaufgaben unterliegt. Sequentielle Verarbeitung von Reaktionsauswahl und visueller Aufmerksamkeit würde Evidenz dafür zeigen, dass beide Prozesse derselben Kapazitätslimitation unterliegen, während parallele Verarbeitung Evidenz dafür zeigen würde, dass beide Prozesse unterschiedlichen Kapazitätslimitationen unterliegen.

Um diese Frage zu untersuchen, wurden Reaktionszeitmaße (locus-of-slack Methode), Targetdetektionsmaße (d') und Ereigniskorrelierte Potentiale (EKPs; N2pc (N2 posterior contralateral)) gemessen. Schwerpunkt aller Analysen war der visuelle Aufmerksamkeitsprozess in einer Konjunktionssuche, die als Aufgabe 2 in Doppelaufgaben implementiert wurde. Aufgabe 1 war stets eine Wahlunterscheidungsaufgabe. Die Verhaltens- und elektrophysiologischen Ergebnisse zeigten, dass die Reaktionsauswahl in Aufgabe 1 und die visuelle Aufmerksamkeit (d.h. Merkmalsbindung) in Aufgabe 2 parallel verarbeitet wurden unabhängig von der Stimulusmodalität in Aufgabe 1, der Schwierigkeit der Reaktionsauswahl in Aufgabe 1 und der Darbietungsform des Stimulusdisplays in Aufgabe 2. Außerdem wurde eine Methode entwickelt, um die Anzahl der Objekte zu berechnen, die parallel zur Reaktionsauswahl verarbeitet wurden. Die Berechnungen stützten die Konklusion, dass die Reaktionsauswahl und die visuelle Aufmerksamkeit unterschiedlichen Kapazitätslimitationen unterliegen.

Schlüsselwörter: visuelle Aufmerksamkeit, visuelle Suche, zentraler Verarbeitungseingpass, Paradigma der Psychologischen Refraktärperiode (PRP), locus-of-slack Methode, Ereigniskorrelierte Potentiale (EKPs), N2pc

List of original research articles

The dissertation is based on three original research articles:

Article 1

Reimer, C. B., Strobach, T., Frensch, P. A., & Schubert, T. (2015). Are processing limitations of visual attention and response selection subject to the same bottleneck in dual-tasks? *Attention, Perception, & Psychophysics*, 77(4), 1052–1069.
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Article 2

Reimer, C. B., Strobach, T., & Schubert, T. (1st revision submitted). Concurrent deployment of visual attention and response selection bottleneck in a dual-task: Electrophysiological and behavioural evidence. *The Quarterly Journal of Experimental Psychology*.

Article 3

Reimer, C. B., & Schubert, T. (submitted). To mask, or not to mask, is not the question: Deploying visual attention to non-masked and masked search displays concurrently to response selection of another task.

1 Introduction

People often experience impaired performance when trying to perform multiple tasks in parallel. For example, they usually drive less focused when they listen to music or chat with a friend at the same time. On the other hand, people also often experience that searching for the object of interest among other objects takes time, for example looking for the keys on a crowded desk or finding the favorite chocolate among other candies.

These everyday examples show that we cannot simultaneously perform as many tasks and attend to as many objects as we would like to. In psychological terms, both response selection and visual attention are limited in capacity. Response selection is required to bind the stimulus information to the corresponding response information before the motor response is executed. As it is assumed that response selection has the characteristic of a central bottleneck (Pashler, 1994; Schubert, 1999; Welford, 1952; but see Meyer & Kieras, 1997a, 1997b; Tombu & Jolicoeur, 2003), the response selection processes in Task 1 and Task 2 of dual-task situations are assumed to operate only for one task at a time. Accordingly, when Task 1 and Task 2 are executed in rapid succession, the reaction time (RT) of Task 2 (RT₂) increases with decreasing temporal interval between both tasks. Concerning visual attention, in some visual search tasks like conjunction search, each item consists of a combination of two features (e.g. color, form). The target consists of a unique feature combination and shares one feature with each distractor. In order to find the target among the distractors, it is assumed that visual attention is required to selectively attend to the items and to bind their features so that the item is identified as the target or a distractor (Treisman & Gelade, 1980; Wolfe, 1994, 2007; Wolfe, Cave, & Franzel, 1989). Correspondingly, search time increases as distractors are added to the search display.

In the last few decades, response selection and visual attention (i.e., feature binding) have been predominately studied separately. However, it is still an open issue whether the processes rely on a common or on distinct capacity limitations. This question is not only of theoretical interest, but it is also relevant considering the multi-tasking demands in everyday life, for example attending to relevant visual information when driving a car or in complex work environments like a cockpit or a hospital. A common capacity limitation would imply that response selection and visual attention

(i.e., feature binding) interfere. That is, response selection and visual attention may process sequentially and/or response selection would impair visual attention deployment. Distinct capacity limitations, however, would imply that response selection and visual attention (i.e., feature binding) do not interfere. That is, response selection and visual attention (i.e., feature binding) may process concurrently and/or response selection would not impair visual attention deployment.

In the present dissertation I investigated this issue by examining response selection and visual attention in a combined approach. In particular, I shed light on the fundamental question whether the capacity limited process in visual attention (i.e., feature binding) is subject to the same bottleneck mechanism as response selection in dual-tasks. In Studies 1-3, I tested under which conditions response selection and visual attention operate sequentially or concurrently using both behavioral and electrophysiological measures. In addition, I developed a method to quantify the amount of visual attention concurrently deployed to the response selection processes. The quantification allowed for calculating how many items of the search display were actually processed concurrently to response selection, which strengthened the conclusions concerning the question whether response selection and visual attention rely on a common or on distinct capacity limitations.

1.1 Overview of the present work

In Chapter 2 the psychological refractory period (PRP) paradigm will be introduced before the central bottleneck model will be described. The conjunction search paradigm and the role of visual attention in feature binding will be explained in Chapter 3. In Chapter 4 previous work on the interplay of response selection and visual attention will be contrasted. The methods applied in Studies 1-3, the locus-of-slack method and the event-related potential (ERP) method to measure the N2pc (N2 posterior contralateral), as well as the research questions of Studies 1-3 will be presented in Chapter 5. Studies 1-3 will be summarized in Chapters 6-8 and discussed in Chapter 9 with regard to implications, limitations, and future research. The method that has been developed in the present dissertation and that allows for quantifying visual attention deployment concurrently to response selection will also be outlined in Chapter 9.

2 Performance in dual-task situations

As previously described, people have difficulties performing two or more tasks at the same time, especially when the tasks involve a choice between two or more response alternatives. Usually, performance is slowed down in at least one of the tasks (for a review of multi-tasking see Fischer & Plessow, 2015). Dual-task paradigms are often used to study the performance deficits in dual-task situations. One of these paradigms is the PRP paradigm. The PRP paradigm is often applied to investigate impaired performance in dual-tasks that consist of two choice discrimination tasks, Task 1 and Task 2. In general, both choice discrimination tasks are rather discrete tasks than continuous tasks. It is relatively easy to decompose discrete tasks into distinct processing stages and infer about their duration, respectively, but this is difficult for continuous tasks. Based on these assumptions, the PRP paradigm allows for applying the locus-of-slack method (Schweickert, 1978, 1980; Chapter 5.1). I applied the locus-of-slack method in Studies 1-3 as it is well suited to investigate if a specific process in Task 2, here feature binding requiring visual attention (Chapters 3.1 and 3.2), operates sequentially or concurrently to the response selection process in Task 1.

2.1 The psychological refractory period (PRP) paradigm and the PRP effect

The PRP paradigm has often been used to study performance in dual-tasks (Pashler, 1994; Welford, 1952). In the PRP paradigm, two discrete choice discrimination tasks, Task 1 and Task 2, are presented with variable temporal intervals (i.e., stimulus onset asynchrony, SOA). Both tasks require fast and accurate responses with priority on Task 1. As is typical for the results, RT2 increases with decreasing SOA. The prolongation of RT2 with shorter SOA is called PRP effect that will be explained below (Pashler, 1994; Schubert, 1999). RT of Task 1 (RT1) is usually not affected by the SOA manipulation.

2.2 Response selection processing in dual-tasks

A variety of theories have been proposed to explain the PRP effect. The central bottleneck model is particularly well established, as it can account for many findings in dual-task research (Pashler, 1994; Schubert, 1999, 2008; Welford, 1952). According to

this model, a discrete choice discrimination task can be decomposed into three distinct processing stages: perception, response selection and motor response. The perceived stimulus information is bound to the corresponding response information at the response selection stage so that the motor response can be executed. In general, perception and motor response are assumed to operate in parallel to the other processing stages, whereas response selection is a central stage that is assumed to operate only for one task at a time. It follows that the response selection stage has the characteristic of a central bottleneck (Pashler, 1994; Schubert, 1999, 2008; Welford, 1952; but see Logan & Gordon, 2001; Meyer & Kieras, 1997a, 1997b; Navon & Miller, 2002; Tombu & Jolicoeur, 2003). Accordingly, at short SOA, response selection in Task 2 is assumed to process only after response selection in Task 1 has been finished. With shorter SOA, response selection in Task 2 is assumed to wait for the end of response selection in Task 1 until it can process. The waiting time – the so-called slack time – is seen in prolonged RT2 with shorter SOA. On the other hand, at long SOA, Task 1 has usually been completed when Task 2 is presented, and Task 2 is assumed to process without interruption.

Alternative models include the strategic bottleneck model (Meyer & Kieras, 1997a, 1997b) and capacity sharing models (Kahneman, 1973; McLeod, 1977; Navon & Gopher, 1979; Navon & Miller, 2002; Tombu & Jolicoeur, 2003, 2005), which have been proposed to explain the PRP effect, but challenge the structural character of the central bottleneck model. Without going into detail, it is important to note that depending on the model, it is actually possible for the response selection processes in a dual-task to operate partially or fully in parallel in certain situations. Irrespective of their differences, virtually all models agree that dual-task performance suffers or may suffer from interference at response selection.

The dual-tasks in Studies 1-3 of the present dissertation are similar to those dual-tasks in which the response selection stages have the characteristic of a central bottleneck. Therefore, it is most likely to assume that the response selection processes in the dual-tasks in Studies 1-3 are processed sequentially. Based on these assumptions I used the PRP paradigm and applied the locus-of-slack method (Schweickert, 1978, 1980; Chapter 5.1) to investigate whether the capacity limited processes in visual attention in a

visual search Task 2 (i.e., feature binding, see below) operate sequentially or concurrently to the response selection processes in a choice discrimination Task 1.

3 Visual attention and visual search

As mentioned in the beginning, in our environment we constantly search for targets like our keys, the button to save a data file or our favorite food in the grocery store. In some situations, we spot the target quickly, but in many situations it takes a while to find it. Visual search paradigms are used to study the fundamental mechanisms of visual attention. As outlined below, in the present dissertation, a conjunction search task was inserted as Task 2 in a PRP paradigm. I used behavioral and electrophysiological measures to reveal whether the response selection processes in Task 1 influence the visual attention processes in the conjunction search Task 2.

3.1 The visual search paradigm and the set size effect

Visual search is the paradigm of choice to study the fundamental mechanisms underlying visual attention (for reviews of visual attention see Carrasco, 2011; Eckstein, 2011; Eimer, 2015). A classic visual search task consists in detecting the presence vs. absence of the target. In a detection task, the search display shows either the target among distractors or only distractors. Usually, the search time (i.e., RT) and the search slopes (i.e., the rate at which the items are processed, ms/item) are measured. The detection task is used in two well-known visual search paradigms called feature search and conjunction search.

In feature search (or pop-out search), the target differs in only one feature from the surrounding distractors, for example a red target among green distractors as shown in Figure 1A (Müller & Krummenacher, 2006; Treisman & Gelade, 1980; Wolfe, 1994, 1998, 2007). The red target is rapidly detected, even as green distractors are added to the search display. Similarly, the absence of the target is quickly reported, irrespective of the number of distractors. In feature search, increasing the set size (i.e., the number of items) does usually not affect the search time (Treisman & Gelade, 1980; Wolfe, 1994, 1998, 2007).

In contrast, in a classic conjunction search task, each item consists of two features. The target consists of a unique feature combination and shares one feature with each distractor, for example a red vertical target among red horizontal and green vertical distractors as shown in Figure 1B. The search time increases as distractors are added to the search display. The increase in search time with larger set size is called set size effect. The set size effect is assumed to reflect that visual attention is limited in capacity as will be outlined in more detail below (Treisman & Gelade, 1980; Wolfe, 1994, 2007; Wolfe, Cave, & Franzel, 1989).

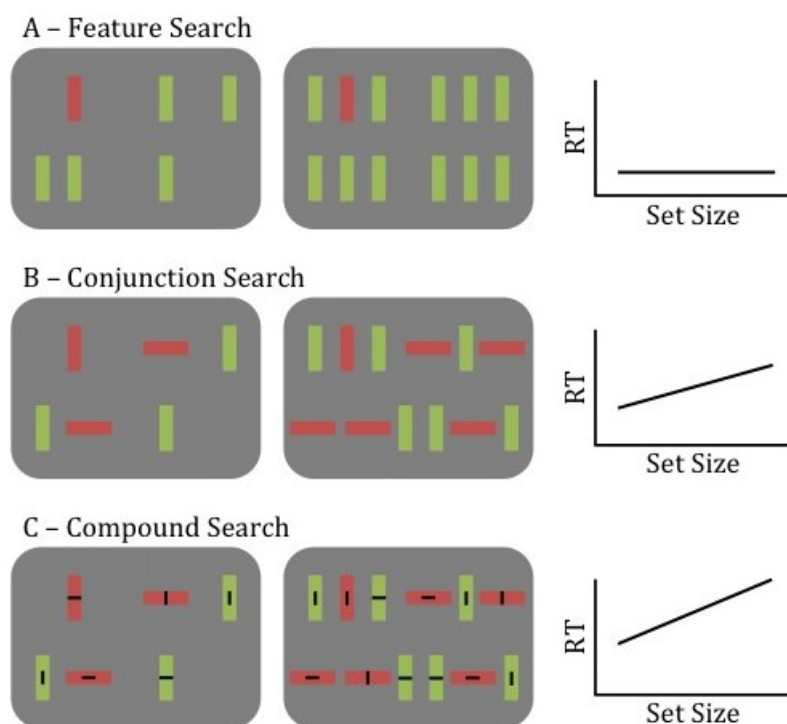


Fig. 1 A: The search displays show a feature search task, here the conditions target present set size 6 and set size 12. Reaction time (RT) does not increase as distractors are added to the search display. B: The search displays show a conjunction search task, here the conditions target present set size 6 and set size 12. RT increases as distractors are added to the search display, which is called set size effect. C: The search displays show a compound search task, here the conditions target present set size 6 and set size 12. RT increases as distractors are added to the search display. The increase is steeper than in the conjunction search task, indicating that the compound task is more visual attention demanding.

When the target is absent in conjunction search, the set size effect is larger than when the target is present, since the criterion to quit a target absent trial differs from the

criterion to stop searching on a target present trial (Wolfe, 1994, 2007, 2012a). Search stops when the target is found, but when the target is absent, search is assumed to stop when a certain threshold is reached. More concrete, search is likely to stop after an unsuccessful search among a subset of items that is usually large enough to contain the target (i.e., activation threshold). Alternatively, search is likely to stop after the target has not been found during a critical time window that is usually long enough to find the target (i.e., time threshold).

I used a conjunction search task in all studies of the present dissertation, because it allowed me to investigate the feature binding process in visual attention that is assumed to be limited in capacity as outlined next.

3.2 The role of visual attention in feature binding

In a classic conjunction search task, the target consists of a unique combination of two features and shares one feature with each distractor, for example a red vertical target among red horizontal and green vertical distractors. Prominent visual search theories propose that focal visual attention selects the items and binds the item features so that an item is correctly identified as the target or a distractor (feature integration theory, Treisman & Gelade, 1980; Treisman & Sato, 1990; guided search model, Wolfe, 1994, 1998, 2007; Wolfe, Cave, & Franzel, 1989; similarity theory, Duncan & Humphreys, 1989, 1992; Humphreys, Hodsoll, Olivers, & Yoon, 2006). It is further assumed that feature binding cannot be performed simultaneously for all items, because the cognitive system is limited with respect to the number of items it can process at the same time. Rather, it is assumed that the items are selectively attended in a serial search process. Accordingly, the search time increases with larger set size. The set size effect is explained by the assumption that visual attention is limited in capacity with respect to feature binding (Treisman & Gelade, 1980; Wolfe, 1994, 2007, 2012b; Wolfe & Bennett, 1997; but see Di Lollo, 2012). On the contrary, feature search does not require attention-consuming feature binding, since the target differs in only one feature from the distractors. That is why feature search is assumed to be performed almost pre-attentively (Treisman & Gelade, 1980; Wolfe, 1994, 2007; Wolfe, Cave, & Franzel, 1989).

Considering response selection and visual attention together, the question arises if the capacity limitation in response selection and the capacity limitation in visual

attention rely on a common or on distinct capacity limitations. In Studies 1-3, I tested under which conditions response selection and visual attention operate sequentially, providing evidence for a common capacity limitation, or concurrently, providing evidence for distinct capacity limitations. In order to strengthen the conclusion on this question, I developed a method to quantify visual attention deployment in dual-tasks. The method allows for calculating the number of items in the search display that are concurrently processed to response selection. The findings of each study will be presented in the Discussion sections of Studies 1-3 (Chapters 6.2, 7.2, 8.2). The details of the method including the calculations will be explained in the General Discussion section (Chapter 9.2).

4 Previous work on the interplay of response selection and visual attention

A few studies have already investigated the interplay of response selection and visual attention. Some authors found evidence for concurrent performance of both processes, which indicated that they rely on distinct capacity limitations (Lien et al., 2011, Experiments 1 & 2; Pashler, 1989, 1991). Other authors, however, reported that response selection affected visual attention deployment, which indicated that both processes rely on a common capacity limitation (Brisson & Jolicoeur, 2007a, 2007b; Lien et al., 2011, Experiments 3 & 4). In the following, the respective dual-task studies will be presented with a focus on the visual attention manipulation. In the conclusion, the factors that are relevant for examining the interplay of response selection and visual attention will be described.

4.1 Evidence that response selection and visual attention rely on distinct capacity limitations

Pashler (1989, Experiment 2) conducted a dual-task experiment in which he combined an auditory two-choice discrimination Task 1 and a visual search Task 2. Both tasks were presented at variable SOAs. The search task required detecting the presence

vs. absence of the target. When the target was absent, each of the eight stimuli positions in the search display was randomly filled with a green O or a red T. When the target was present, a randomly selected item was replaced with a green T. The search display was masked after a brief exposure. Accordingly, visual attention could only be deployed during a short period of time until the mask terminated any sensory processing (Cameron, Tai, Eckstein, & Carrasco, 2004; Palmer & McLean, 1995; Wolfe, 2007). Concerning the analysis, Pashler focused on the accuracy in the target detection task. The author found similar target detection accuracy at short and at long SOA. He concluded that response selection and visual attention operated concurrently (see also De Jong & Sweet, 1994).

In addition, Pashler (1991) conducted another series of dual-task experiments to disentangle interference between response selection and visual attention shifts. In Experiment 1, Task 1 required an auditory two-choice discrimination. In Task 2, visual attention was shifted from fixation to a probe. The probe was a short horizontal line that marked the target letter in a letter display. The task was to report the probed target letter. The search display was masked after a brief exposure. Pashler focused on target report accuracy. The author did not find an effect of SOA, indicating that accuracy was similar at short and at long SOA. In the following experiments, Pashler manipulated the relation between the probe and the target to measure whether the response selection processes in Task 1 influenced the visual attention shifts in Task 2. He concluded that overall, the findings were in line with the assumption that the visual attention shifts in Task 2 operated independently of the response selection processes in Task 1.

Interestingly, Lien et al. (2011) provides evidence for both concurrent and sequential processing of response selection and visual attention. The authors found concurrent processing of response selection and visual attention when Task 1 required a two-choice discrimination (i.e., easy response selection, Experiments 1 & 2), but they found sequential processing of response selection and visual attention when Task 1 required a four-choice discrimination (i.e., difficult response selection, Experiments 3 & 4). The influence of the response selection difficulty in Task 1 on visual attention deployment in Task 2 will be discussed below. In the study of Lien et al., the search display contained four letters (i.e., two Ts and two Ls). The target letter (i.e., red) differed in color from the distractor letters (i.e., one green and two white letters). The task

consisted in identifying the target letter (i.e., T vs. L). The visual search display was masked after a brief exposure. Lien et al. analyzed the N2pc, an ERP that indexes visuo-spatial attention allocation (Eimer, 1996; Luck & Hillyard, 1994a, 1994b; Woodman & Luck, 1999, 2003). To understand the authors' reasoning, it should be briefly explained that the N2pc amplitude is linked to the amount of visual attention that is allocated to the target in a visual search task and the N2pc latency is linked to the speed of the visual attention shift (Woodman & Luck, 1999, 2003). The N2pc will be explained in detail in Chapter 5.2. Lien et al. locked the N2pc to the onset of the search display and compared the amplitude across SOAs. When Task 1 required an auditory two-choice discrimination, the N2pc amplitude was similar across SOAs (Experiment 1). The response selection processes in Task 1 did not affect the amount of visual attention that was allocated to the target in Task 2 so that a similar amount of visual attention was allocated to the target at every SOA. The authors concluded that visual attention was deployed in parallel to the easy response selection processes.

Lien et al. also found this result when Task 1 was a visual two-choice discrimination task (2011, Experiment 2). In Experiment 2, both Task 1 and Task 2 drew on the same visual attentional capacity making interference between both tasks more likely compared to Experiment 1 (see Magen & Cohen, 2010; Wickens, 2008; Wickens & Liu, 1988). However, Lien et al. showed that even when the stimulus modalities in both tasks overlapped, visual attention in Task 2 was concurrently deployed to the response selection processes in the visual Task 1. The authors concluded that when both tasks drew on the same visual attentional capacity, easy response selection processes do not influence visuo-spatial attention allocation (Experiments 1 & 2). In Study 1 (Chapter 6) it was also investigated whether the stimulus modality in Task 1 (i.e., auditory vs. visual) influences visual attention deployment in a conjunction search Task 2.

4.2 Evidence that response selection and visual attention rely on a common capacity limitation

In contrast, Lien et al. (2011, Experiments 3 & 4) found interference between response selection in Task 1 and visual attention deployment in Task 2 when Task 1 required a four-choice discrimination instead of a two-choice discrimination. They used the same search task as described above and analyzed the N2pc amplitude again. This

time, the N2pc amplitude was reduced at short SOA compared to long SOA. The authors reasoned that less visual attention could be deployed to the target when response selection in Task 1 was difficult. Altogether, Lien et al. showed that response selection and visual attention operated concurrently when response selection was easy (i.e., two-choice discrimination, Experiments 1 & 2), but sequentially when response selection was difficult (i.e., four-choice discrimination, Experiments 3 & 4). The authors found interference between difficult response selection in Task 1 and visual attention in Task 2 for both auditory and visual four-choice discrimination Tasks 1. Thus, increasing the response selection difficulty in Task 1 from a two-choice to a four-choice discrimination is likely to impair visual attention deployment in Task 2. Study 3 examined the influence of difficult compared to easy response selection processes on visual attention deployment (Chapter 8).

Brisson and Jolicoeur (2007a, 2007b) also showed that response selection and visual attention deployment interfere. They conducted electrophysiological dual-task studies, in which they combined an auditory four-choice discrimination Task 1 with a visual search Task 2 at short and at long SOA. In Task 2, the four visual stimuli were squares with a gap at one side (i.e., left, right, up or down). The target (i.e., red) differed in color from the distractors (i.e., green). The visual search task required localizing the target and identifying the gap (i.e., four-choice discrimination). In most of the experiments, the search display was masked after a brief exposure. The authors focused on the N2pc to measure visual attention deployment. They locked the N2pc to the search display onset and compared the amplitude across SOAs. The N2pc amplitude was reduced at short SOA compared to long SOA. The authors concluded that less visual attention could be allocated to the target at short SOA compared to long SOA showing interference between difficult response selection in Task 1 and visual attention deployment in Task 2. In contrast to Lien et al. (2011), Brisson and Jolicoeur did not manipulate the response selection difficulty in Task 1.

4.3 Conclusion: Factors that are relevant when examining the interplay of response selection and visual attention

Based on the described studies (Brisson & Jolicoeur, 2007a, 2007b; Lien et al., 2011; Pashler, 1989, 1991), four factors seem to be particularly important when

studying the interplay of response selection and visual attention: the type of presentation of the search display in Task 2, the stimulus modality in Task 1, the response selection difficulty in Task 1, and the visual attention process in the search Task 2 that is used to investigate interference.

Firstly, in most of the authors' studies the search display was masked after a brief exposure (Brisson & Jolicoeur, 2007a, 2007b; Lien et al., 2011; Pashler, 1989, 1991). When the search display is masked, visual attention can only be deployed during a critical time window until the mask disrupts any sensory processing (Cameron, Tai, Eckstein, & Carrasco, 2004; Palmer & McLean, 1995; Wolfe, 2007). It follows that the authors focused on fast spatial shifts of visual attention. In contrast, the present dissertation investigated the open issue of whether response selection and visual attention interfere when the search display is presented until response (i.e., non-masked) and visual attention is deployed in a serial search process around the display (Treisman & Gelade, 1980; Wolfe, 1994, 2007).

Concerning the stimulus modality in Task 1, interference between Task 1 and the visual search Task 2 should be more likely to occur when both tasks draw on the same visual attentional capacity (i.e., same stimulus modality in both tasks) compared to when both tasks draw on distinct visual attentional capacities (i.e., different stimulus modalities in both tasks) (Magen & Cohen, 2010; Wickens, 2008; Wickens & Liu, 1988). Interestingly, Lien et al. (2011, Experiments 1 & 2) showed concurrent performance of Task 1 and Task 2 in both dual-task situations. In Study 1 (Chapter 6), the stimulus modality in Task 1 was manipulated to investigate whether an auditory and/or a visual Task 1 influences visual attention deployment (i.e., feature binding) in a conjunction search Task 2.

In addition, Lien et al. (2011) manipulated the response selection difficulty in Task 1. The authors found concurrent response selection and visual attention processing when Task 1 was easy (i.e., two-choice discrimination) (Experiments 1 & 2; see also Pashler, 1989, 1991), but they found sequential processing when Task 1 was difficult (i.e., four-choice discrimination) (Experiments 3 & 4; Brisson & Jolicoeur, 2007a, 2007b). In Study 3 (Chapter 8), the response selection difficulty in Task 1 was manipulated to examine the influence on visual attention deployment (i.e., feature binding) in Task 2. To extend these findings, I combined an easy and a difficult Task 1 not only with a masked

conjunction search Task 2, but also with a non-masked conjunction search Task 2 (i.e., search display presented until response), respectively.

The visual attention processes in the search tasks of Brisson and Jolicoeur (2007a, 2007b) and of Lien et al. (2011) have to be considered in more detail. Two aspects are important. First, both tasks are so-called compound search tasks. In compound search tasks, the target-defining attributes do not depend on the response-defining attributes (Müller & Krummenacher, 2006). Put differently, a compound task requires a target-related and a response-related visual attention process. The search tasks in the studies of Brisson and Jolicoeur as well as of Lien et al. consisted of the localization of the target and the discrimination of a specific target attribute, which was response relevant. At first glance it is unclear which of the two processes interfered with difficult response selection in Task 1 or if it is only the combination of both processes that led to interference. In order to provide evidence on the question which visual attention process interfered with (difficult) response selection, interference should be examined for one visual attention process at a time. More concretely, interference should be examined separately for the target-related process, the localization of the target and the response-related process, the discrimination of a specific target feature. Second, considering the search tasks in the studies of Brisson and Jolicoeur and of Lien et al. in more detail, it is plausible to assume that the response-related process in contrast to the target-related process interfered with difficult response selection. Since the target differed in color from the distractors (i.e., feature search), it is plausible to assume that it automatically captured attention. In turn, it is very likely that the automatic capture facilitated the target localization. On the other hand, the additional discrimination process of a specific target feature required probably more visual attention, which could explain why the authors found interference.

As outlined below, in Studies 1-3, a conjunction search task was used to study interference between response selection and visual attention. Brisson and Jolicoeur (2007a, 2007b; see also Lien et al., 2011) chose search tasks in which it was possible to localize the target via automatic capture of attention. In the conjunction search task, however, the target is localized via feature binding that is assumed to be limited in capacity (Pashler, 1989; Treisman & Gelade, 1980; Wolfe, 1994, 2007). Therefore their studies and my own focused on visual attention processes that are qualitatively different.

5 Methods and research questions of Studies 1, 2, and 3

The studies of the present dissertation focused on interference between response selection and visual attention, and with respect to visual attention in particular on the feature binding processes in a conjunction search task. The set size effect in conjunction search time is assumed to indicate that visual attention is limited in capacity (Treisman & Gelade, 1980; Wolfe, 1994, 2007; Wolfe, Cave, & Franzel, 1989). Selectively attending to an item and binding the item features constitutes a bottleneck in visual attention. The conjunction search task is therefore well suited to investigate interference between visual attention and response selection, a processing stage that is also assumed to constitute a bottleneck (Pashler, 1994; Schubert, 1999; Welford, 1952). Accordingly, implementing a conjunction search task as Task 2 in a PRP dual-task allowed for addressing the question whether response selection and visual attention rely on a common or on distinct capacity limitations.

In Studies 1-3, I applied the locus-of-slack method (Schweickert, 1978, 1980) and in Study 2, I also measured the N2pc (Eimer, 1996; Luck & Hillyard, 1994a, 1994b; Woodman & Luck, 1999, 2003) to investigate whether visual attention is subject to the same bottleneck mechanism as response selection in dual-tasks. The locus-of-slack method has never been applied in the context of interference between response selection and visual attention (i.e., feature binding) (for successful applications of the locus-of-slack method in other contexts see for example Fischer, Miller, & Schubert, 2007; Hein & Schubert, 2004; Johnston & McCann, 2006; Johnston, McCann, & Remington, 1995; McCann & Johnston, 1992; Pashler & Johnston, 1989; Schubert, Fischer, & Stelzel, 2008). Below, the locus-of-slack method and the N2pc will be explained before the research questions of Studies 1-3 will be presented.

5.1 Behavioral method: the locus-of-slack method

The locus-of-slack method (Schweickert, 1978, 1980) is well suited to localize bottlenecks in dual-task situations. In the present dissertation, the locus-of-slack method was applied to test whether visual attention required for feature binding is subject to the same bottleneck mechanism as response selection in dual-tasks. As shown in Figure 2,

the locus-of-slack method allowed for testing whether response selection and visual attention operate sequentially or concurrently. In order to test these hypotheses in Studies 1-3, the dual-tasks consisted of a choice discrimination Task 1 and a conjunction search Task 2 that were presented at variable SOAs. The conjunction search task required target detection in displays of different set sizes. The analyses focused on the effects of the SOA and set size manipulation as well as the SOA and display type manipulation on RT2 (i.e., the search time), respectively.

Concerning the factors SOA and set size, the hypotheses according to the locus-of-slack method were as follows: If visual attention is subject to the same bottleneck mechanism as response selection in dual-tasks, the set size effect (i.e., the increase in RT2 from the small to the large set size) would be similar at short and at long SOA (Figure 2A). The effect of set size would be additive with the effect of SOA, which would indicate sequential processing of response selection and visual attention (i.e., feature binding). In more detail, at short SOA, visual attention deployment in Task 2 would have to wait and could only start after response selection in Task 1 would have been completed, because both processes would rely on a common capacity limitation. At long SOA, the temporal interval between both tasks would be long enough so that Task 2 would be processed without any interruption after Task 1 would have been completed. Accordingly, the additional time for processing the large set size compared to the small set size would prolong RT2 for the same amount both at short and at long SOA. An additive effect of SOA and set size would provide evidence for the assumption that response selection and visual attention (i.e., feature binding) rely on a common capacity limitation.

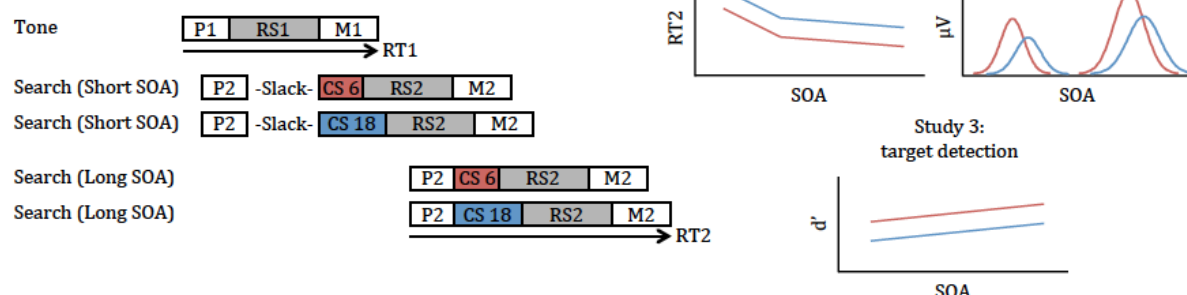
If however, visual attention is not subject to the same bottleneck mechanism as response selection in dual-tasks, the set size effect at short SOA would be significantly reduced compared to the set size effect at long SOA (Figure 2B). The resulting underadditive interaction of SOA and set size would indicate concurrent processing of response selection and visual attention (i.e., feature binding). In more detail, at short SOA, visual attention in Task 2 would not have to wait until response selection in Task 1 would have been completed. Rather, visual attention could be deployed concurrently to response selection, because both processes would rely on distinct capacity limitations. The additional processing time for the large compared to the small set size would be

absorbed into the slack time and would not prolong RT2 at short SOA. At long SOA, the temporal interval between both tasks would be long enough so that Task 1 would have been completed before Task 2 processing would start. Absorption is not possible at long SOA and the additional processing time for the large set size compared to the small set size would be added to RT2. An underadditive interaction of SOA and set size would provide evidence for the assumption that response selection and visual attention (i.e., feature binding) rely on distinct capacity limitations. Note that it is possible that visual search time is not fully, but only partially absorbed into the slack time. The implication of a partial absorption will be discussed in the Discussion sections of Studies 1-3 and the General Discussion section. However, in order to find an underadditive interaction, it is important that the set size effect at short SOA is significantly reduced compared to the set size effect at long SOA.

The same hypotheses were tested for the factors SOA and display type. The factor display type reflected the manipulation of the target present vs. target absent decision, which implies additional processing time in target absent search compared to target present search (Chapters 3.1 & 3.2).

Based on the locus-of-slack method, I developed a method to quantify visual attention deployment concurrently to response selection in dual-tasks. Calculating how many items were actually processed concurrently to response selection shed more light on the question whether response selection and visual attention rely on a common or on distinct capacity limitations. The findings will be presented in the Discussion sections of Studies 1-3 (Chapters 6.2, 7.2, 8.2). The details of the method including the calculations will be explained in the General Discussion section (Chapter 9.2).

A – Response selection and visual attention operate sequentially, indicating that they rely on a common capacity limitation



B – Response selection and visual attention operate concurrently, indicating that they rely on distinct capacity limitations

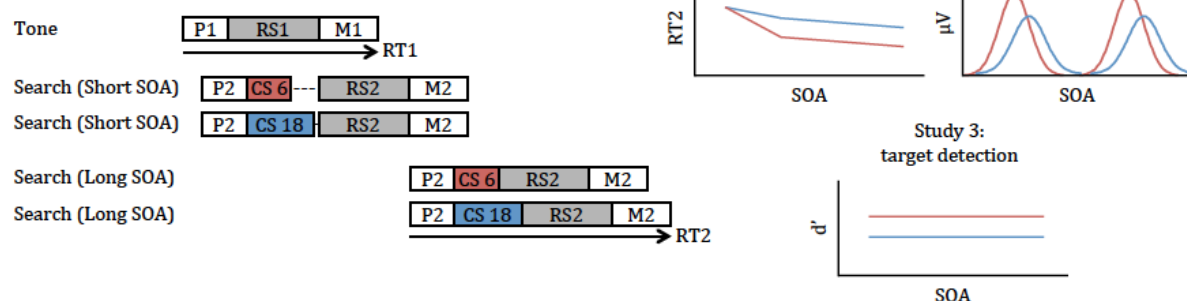


Fig. 2 A: If visual attention is subject to the same bottleneck mechanism as response selection in dual-tasks, additive effects of Stimulus Onset Asynchrony (SOA) and set size on reaction time of Task 2 (RT2) should result (Studies 1-3). In addition, the N2pc parameters would depend on SOA as reflected by a reduced amplitude at short SOA compared to long SOA (simplified hypothesis representation of the N2pc parameters) (Study 2). Furthermore, target detection performance d' should be decreased at short SOA compared to long SOA (Study 3). The set size manipulation in the visual search Task 2 is illustrated by two different set sizes. B: If visual attention is not subject to the same bottleneck mechanism as response selection in dual-tasks, underadditive interactions of SOA and set size on RT2 should result (Studies 1-3). In addition, the N2pc parameters would be independent of SOA as reflected by similar amplitudes at short SOA and at long SOA (simplified hypothesis representation of the N2pc parameters) (Study 2). Furthermore, target detection performance d' should be similar at short SOA and at long SOA (Study 3). The set size manipulation in the visual search Task 2 is illustrated by two different set sizes.

RT1 = reaction time to Task 1; P1 = perception stage of Task 1; RS1 = response selection stage of Task 1; M1 = motor stage of Task 1; RT2 = reaction time to Task 2; P2 = perception stage of Task 2; CS 6/18 = conjunction search set size 6/18; RS2 = response selection stage of Task 2; M2 = motor stage of Task 2.

5.2 Event-related potential method: the N2pc, an ERP associated with visuo-spatial attention deployment

As outlined in Chapter 4, the N2pc has been used to investigate interference between response selection and visual attention (Brisson & Jolicoeur, 2007a, 2007b; Lien et al., 2011). In Study 2 (Chapter 7), I measured the N2pc in combination with the locus-of-slack method to examine interference between response selection and visual attention.

The N2pc is an ERP of visuo-spatial attention deployment, specifically of the spatial selection of the target in visual search arrays (Eimer, 1996; Luck & Hillyard, 1994a, 1994b; Woodman & Luck, 1999, 2003). Magnetoencephalographic (MEG) recordings suggest that the N2pc is generated primarily in inferior occipitotemporal cortex and has probably an early parietal contribution (Hopf, Boelmans, Schoenfeld, Heinze, & Luck, 2002; Hopf et al., 2000). In particular, the electrophysiological marker is elicited as a negative-going deflection over parietal areas around 180-280 ms after onset of the visual stimuli.

In order to measure the N2pc, the stimuli in the search display are balanced, that is target and distractors are equally presented to the ipsilateral and contralateral visual fields. The N2pc is more negative at electrodes contralateral to the side of the attended stimulus (i.e., the target) compared to ipsilateral. The N2pc difference wave is derived from subtracting the waveforms recorded ipsilateral to the attended stimulus from the waveforms recorded contralateral to the attended stimulus. When the stimuli are balanced, the subtraction procedure eliminates any activity (i.e., pure sensory activity, any higher-level cognitive activity equal for ipsilateral and contralateral targets) that is not attributable to the visual attention processes.

The specific hypotheses regarding the N2pc parameters will be presented in the summary of Study 2 (Chapter 7). The hypotheses were derived from the assumptions that the amplitude is linked to the amount of visual attention allocated to the target in a visual search task, the peak latency is linked to the speed of the visual attention shift to the target and the onset latency is linked to the onset of target selection (Luck & Hillyard, 1994a, 1994b; Woodman & Luck, 1999, 2003).

5.3 Research questions of Studies 1, 2, and 3

Following the state of the art on the interplay of response selection and visual attention (Chapter 4), some questions remained unanswered. They were addressed in Studies 1-3 and related to the question whether visual attention required for feature binding is subject to the same bottleneck mechanism as response selection in dual-tasks as follows:

- 1) Does response selection in Task 1 influence visual attention deployment in Task 2 in dual-tasks (a) in which the stimulus modalities differ across tasks (i.e., auditory Task 1, visual Task 2) and (b) in dual-tasks in which the stimulus modality is the same in both tasks (i.e., visual Task 1, visual Task 2)? (Study 1)
- 2) Electrophysiology (i.e., ERPs) has a higher temporal resolution than behavioral measures. Because an investigation on possible interference between response selection in Task 1 and visual attention deployment in Task 2 is highly time-sensitive, I asked whether the N2pc analysis reveals the same or different results concerning visual attention deployment compared to the RT2 analysis according to the locus-of-slack method? (Study 2)
- 3) Do difficult compared to easy response selection processes in Task 1 impair (a) visual attention deployment in Task 2 in a serial search process (i.e., non-masked search display) and (b) target detection performance in Task 2 when the search display is masked, respectively? (Study 3)

In Chapters 6-8, these questions and the corresponding hypotheses will be described in more detail followed by a summary of each study. The original publications of Studies 1-3 can be found in Appendices A-C.

6 Study 1 ‘Are processing limitations of visual attention and response selection subject to the same bottleneck in dual-tasks?’

A few studies investigated interference between response selection and visual attention (Brisson & Jolicoeur, 2007a, 2007b; Lien et al., 2011; Pashler, 1989, 1991). In almost all of the studies, the search displays were masked and the authors focused on the question whether response selection affected the initial visual attention shift to the search display. It remained an open issue to investigate interference between response selection and visual attention when the search display is presented until response (i.e., non-masked) and visual attention is deployed in a serial search process.

6.1 Research question and Method

Study 1 (attached in Appendix A) consisted of two PRP dual-task experiments. In both experiments, the search display of the conjunction search Task 2 was presented until response (i.e., non-masked) to focus on visual attention deployment (i.e., feature binding) in a serial search process. In Experiment 1, Task 1 was an auditory two-choice discrimination task (i.e., low vs. high tone discrimination) and in Experiment 2, Task 1 was a visual two-choice discrimination task (i.e., yellow vs. blue color discrimination). Study 1 addressed the question whether visual attention deployment in a serial search process is subject to the same bottleneck mechanism as response selection in dual-tasks (a) when the stimulus modalities differ across tasks (Experiment 1) and (b) when the stimulus modality is the same in both tasks (Experiment 2).

Following the assumptions of Wickens’s multiple resource model (2008; Wickens & Liu, 1988) and the assumptions of the dimension action model, a modality specific interference model (Magen & Cohen, 2010), interference was expected between the visual Task 1 and the conjunction search Task 2 (Study 1, Experiment 2). Since stimuli in the same modality are expected to draw on the same attentional capacity, interference between the visual Task 1 and the conjunction search Task 2 was likely to occur at the stimulus processing stages. On the contrary, interference between the auditory stimuli in Task 1 and the visual stimuli in Task 2 should not occur at the stimulus processing

stages, because the stimuli were in different modalities and drew on different attentional capacities (Study 1, Experiment 1).

In both experiments of Study 1, the conjunction search Task 2 required target detection in displays of three set sizes (i.e., set sizes 6, 12, & 18; task adapted from Wolfe, Palmer, & Horowitz, 2010). The search display was presented until response (i.e., non-masked) and RT2, the search time, was measured. The four SOAs between Task 1 and Task 2 varied between 50 ms and 800 ms. In Experiment 1, Task 1 required an auditory two-choice discrimination and in Experiment 2, Task 1 required a visual two-choice discrimination. The participants were asked to respond as fast and as accurately as possible to both tasks with priority on Task 1.

In both experiments, the locus-of-slack method (Schweickert, 1978, 1980) was applied to test two hypotheses regarding sequential vs. concurrent processing of response selection and visual attention (i.e., feature binding) (Chapter 5.1). If visual attention is subject to the same bottleneck mechanism as response selection in dual-tasks, the effect of set size would be additive with the effect of SOA (Figure 2A). The set size effect would be similar at short and at long SOA, indicating that at short SOA, the visual attention processes in Task 2 (i.e., feature binding) could only start after the response selection processes in Task 1 would have been finished. This finding would provide evidence for the assumption that response selection and visual attention rely on a common capacity limitation. On the other hand, if visual attention is not subject to the same bottleneck mechanism as response selection in dual-tasks, the interaction of SOA and set size would be underadditive (Figure 2B). The set size effect at short SOA would be significantly reduced compared to the set size effect at long SOA, as visual search time would be absorbed into the slack time at short SOA. An underadditive interaction would indicate that the visual attention processes in Task 2 (i.e., feature binding) operate concurrently to the response selection processes in Task 1. This finding would provide evidence for the assumption that response selection and visual attention rely on distinct capacity limitations.

The hypotheses were not only tested for the factors SOA and set size, but also for the factors SOA and display type. The factor display type reflected the manipulation of the target present vs. target absent detection (Chapters 3.1 & 3.2).

The same hypotheses were tested in Experiment 1 and in Experiment 2. However, in Experiment 2, it was more likely to find sequential processing of response selection and visual attention. Interference is more likely to be expected when the stimuli in Task 1 and Task 2 are in the same modality and draw on the same visual attentional capacity (Magen & Cohen, 2010; Wickens, 2008; Wickens & Liu, 1988).

6.2 Results and Discussion

Most important for the research question, there was an underadditive interaction of SOA and set size in Experiment 1 that is shown in Figure 3 (the statistical results can be found in the original research article, please see Appendix A; the same holds for Studies 2-3, please see Appendices B-C). A comparison between the set size effects (i.e., RT2 difference between the large and the small set size) at long SOA (Mean (M) = 99 ms) and at short SOA (M = 38 ms) showed that the set size effect was significantly reduced at short SOA. Thus, visual search time was absorbed into the slack time. In addition, there was an underadditive interaction of SOA and display type. The RT2 difference between target absent and target present was significantly smaller at short SOA (M = 17 ms) compared to long SOA (M = 23 ms). Both interactions indicated that the visual attention processes in the conjunction search Task 2 (i.e., feature binding) operated concurrently to the response selection processes in the auditory two-choice discrimination Task 1.

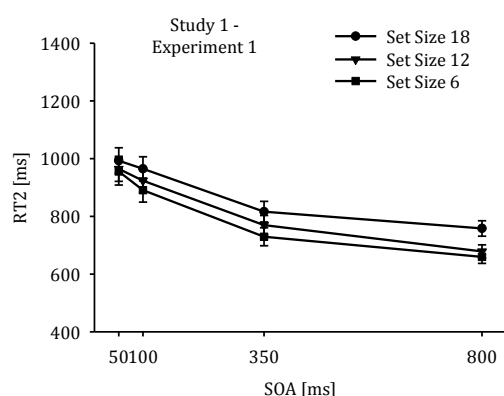


Fig. 3 Study 1, Experiment 1: Reaction time of the conjunction search Task 2 (RT2) depending on Stimulus Onset Asynchrony (SOA) and set size (6, 12, and 18) collapsed across the target present and target absent condition. Error bars represent standard error of the mean.

In Experiment 2, there was also an underadditive interaction of SOA and set size. A comparison between the set size effects at long SOA ($M = 111$ ms) and at short SOA ($M = 53$ ms) revealed that the set size effect was significantly reduced at short SOA. Visual search time was again absorbed into the slack time. There was also an underadditive interaction of SOA and display type. The RT2 difference between target absent and target present was significantly smaller at short SOA ($M = 3$ ms) compared to long SOA ($M = 68$ ms). Again, visual search time was absorbed into the slack time. There was also an interaction of the factors SOA, set size, and display type, which pointed to different SOA and set size interactions for target present and target absent. Indeed, the SOA and set size interaction was significant for target present, but the interaction was not significant for target absent. A closer look at the underadditive interaction for target present showed that the set size effect at short SOA ($M = 29$ ms) was significantly reduced compared to the set size effect at long SOA ($M = 100$ ms).

Taken together in Experiment 2, the underadditive interactions (i.e., SOA \times set size and SOA \times display type) revealed that the visual attention processes in the conjunction search Task 2 (i.e., feature binding) operated concurrently to the response selection processes in the visual two-choice discrimination Task 1. Visual search time was absorbed into the slack time when the target was present, but visual search time was only partially absorbed when the target was absent. I will get back to this issue in the Discussion section below and in the General Discussion section (Chapter 9.2).

To summarize these results, Experiments 1 and 2 provided evidence for the assumption that regardless of the stimulus modality in Task 1 visual attention in Task 2 was concurrently deployed to response selection in Task 1. In both experiments, visual search time was absorbed into the slack time, yet absorption was larger in Experiment 1 than in Experiment 2. Thus, the results of Study 1 showed that visual attention (i.e., feature binding) and response selection rely on distinct capacity limitations.

To discuss Study 1, in both experiments visual search time was absorbed into the slack time, indicating that visual attention in Task 2 operated concurrently to response selection in Task 1. The absorbed search time corresponds to the number of items that were processed during the slack time. It is of interest to calculate the number of items to quantify visual attention that was concurrently deployed to response selection.

Quantifying visual attention also reveals more about the deployment of visual attention when visual search time is only partially absorbed. In the present dissertation, I developed such a quantification method that is based on an innovative application of the locus-of-slack method.

As the method including the calculations will be explained in the General Discussion section (Chapter 9.2), it should be sufficient to say for the discussion of Study 1 that in Experiment 1 consisting of an auditory two-choice discrimination Task 1 and a conjunction search Task 2, 14.25 of 18 items were processed during the slack time when the target was present and 12.75 items of 18 items when the target was absent. In Experiment 2 consisting of a visual two-choice discrimination Task 1 and a conjunction search Task 2, 14.51 of 18 items were processed during the slack time when the target was present and 10.47 of 18 items when the target was absent. In both experiments, almost all items were processed during the slack time when the target was present and still more than half of the items when the target was absent. Thus, visual attention deployment was similar in target present trials irrespective of the stimulus modality overlap in Task 1 and Task 2, since in both experiments, a similar number of items were processed during the slack time. However, in target absent trials, fewer items (2.28 items) were processed during the slack time when the stimulus modalities overlapped in both tasks. It is therefore likely to assume that when both tasks drew on the same visual attentional capacity, the participants searched among a smaller group of items than in Experiment 1 before deciding to quit search (Wolfe, 1994, 2007, 2012a).

Recently, other authors investigated interference between response selection and visual attention (Brisson & Jolicoeur, 2007a, 2007b; Lien et al., 2011; Pashler, 1989, 1991). In most of their studies, the search displays were masked and the authors focused on the initial visual attention shift to the search display. Lien et al. (Experiments 1 & 2) and Pashler showed that the response selection processes in a two-choice discrimination task did not impair the initial visual attention shift to the search display. In Study 1, the search display was presented until response (i.e., non-masked) to measure visual attention deployment in a serial search process. The locus-of-slack method revealed that the response selection processes in a two-choice discrimination task did not impair the feature binding processes in a serial search task. The results thus extended the findings of Lien et al. (Experiments 1 & 2) and of Pashler.

Moreover, Study 1 investigated whether the stimulus modality in Task 1 influences interference between response selection and visual attention. Whereas Experiment 1 was a cross-modal dual-task consisting of an auditory Task 1 and a conjunction search Task 2, the tasks in Experiment 2 were both visual, that is a color discrimination Task 1 and a conjunction search Task 2. The results indicated that regardless of the stimulus modality in Task 1, visual attention operated concurrently to response selection. Even when the stimuli in both tasks drew on the same visual attentional capacity, performing the two-choice color discrimination Task 1 did not impair the binding of color and form features in Task 2. The results were in line with the findings of Lien et al. (2011, Experiments 1 & 2), who also showed concurrent performance of response selection and visual attention regardless of the stimulus modality in Task 1.

However, the results of Experiment 1 contradicted the findings of Brisson and Jolicoeur (2007a, 2007b; see also Lien et al., 2011, Experiments 3 & 4). The authors found interference between response selection and visual attention. They used an auditory four-choice discrimination Task 1, which is more difficult to perform than an auditory two-choice discrimination Task 1. It has to be investigated whether difficult response selection impairs visual attention (i.e., feature binding) in the conjunction search task. I will get back to this issue in Study 3 and in the General Discussion section.

7 Study 2 ‘Concurrent deployment of visual attention and response selection bottleneck in a dual-task: Electrophysiological and behavioural evidence’

As outlined in the previous chapter, the results of Study 1 provided evidence for the assumption that response selection and visual attention rely on distinct capacity limitations (see also Lien et al., 2011, Experiments 1 & 2; Pashler, 1989, 1991). However, the results differed from the findings of Brisson and Jolicoeur (2007a, 2007b; see also Lien et al., Experiments 3 & 4). The authors focused on the N2pc to examine interference

between response selection and visual attention. The N2pc is an ERP that indexes visuo-spatial attention deployment (Eimer, 1996; Luck & Hillyard, 1994a, 1994b; Woodman & Luck, 1999, 2003). As mentioned above, the N2pc amplitude is linked to the amount of visual attention that is allocated to the target in a visual search task (Woodman & Luck, 1999, 2003). In the studies of the authors, the N2pc amplitude was reduced at short SOA compared to long SOA. They concluded that response selection and visual attention interfere.

In this context, it remained open whether an N2pc analysis reveals the same or different results concerning visual attention deployment compared to an RT2 analysis based on the locus-of-slack method. Both methodologies measure temporal information, yet with different resolutions. The temporal information of all task processes is integrated in one data point in RT measures, whereas ERPs are markers of particular task processes like visual attention. In Study 2 behavioral measures and the ERP technique were combined. I applied the locus-of-slack method and measured the N2pc to investigate the interplay of response selection and visual attention (i.e., feature binding) in a serial search process.

7.1 Research question and Method

In Study 2 (attached in Appendix B), the main experiment was a PRP dual-task to investigate interference between response selection and visual attention required for feature binding in a serial search process. Both the N2pc and the visual search time were measured to address the question whether the N2pc analysis reveals the same or different results concerning visual attention deployment compared to the RT2 analysis based on the locus-of-slack method.

The dual-task experiment consisted of the following tasks. The conjunction search Task 2 required target detection in displays of two set sizes (i.e., set sizes 8 & 16; task adapted from Wolber & Wascher, 2003) and the search display was presented until response (i.e., non-masked). Task 1 required an auditory two-choice discrimination. The three SOAs between Task 1 and Task 2 varied between 60 ms and 800 ms. The participants were asked to respond as fast and as accurately as possible to both tasks with priority on Task 1.

Concerning the behavioral measures, the locus-of-slack method (Schweickert, 1978, 1980) was applied to test two hypotheses regarding sequential vs. concurrent processing of response selection and visual attention (i.e., feature binding) (Chapter 5.1, Figure 2). The hypotheses for the factors SOA and set size as well as for the factors SOA and display type were identical to the hypotheses in Study 1 (see Chapter 6.1).

The N2pc was measured in addition to RT2 (Chapter 5.2). The N2pc was locked to the onset of the search display and the amplitude, peak latency and onset latency were analyzed. The hypotheses were based on the assumptions that the amplitude is linked to the amount of visual attention allocated to the target in a visual search task, the peak latency is linked to the speed of the visual attention shift to the target, and the onset latency is linked to the onset of target selection (Luck & Hillyard, 1994a, 1994b; Woodman & Luck, 1999, 2003). As shown in Figure 2A, if the response selection processes in Task 1 affect the amount of visual attention that could be allocated to the target, the amplitude would be attenuated at short SOA compared to long SOA. If the response selection processes in Task 1 delay the visual attention shift to the target in Task 2, the peak latency would be prolonged at short SOA compared to long SOA. Likewise, if the response selection processes in Task 1 delay the onset of target selection, the onset latency would be prolonged at short SOA compared to long SOA. Taken together, in case response selection and visual attention rely on a common capacity limitation, the N2pc parameters would change as a function of SOA (Figure 2A). However, in case they rely on distinct capacity limitations, the N2pc parameters would be independent of SOA (Figure 2B).

Finally, the conjunction search task was presented as single-task and the N2pc was measured to compare visual attention deployment in the single-task and visual attention deployment in the dual-task. The comparison allowed for answering the question whether general dual-task demands (i.e., the demands which arise from the general need to perform an additional task (Jiang, Saxe, & Kanwisher, 2004; Schubert & Szameitat, 2003; Töllner, Strobach, Schubert, & Müller, 2012)) affect visual attention deployment per se. If general dual-task demands influence visual attention deployment, the N2pc amplitude would be attenuated in the dual-task compared to the single-task and the peak and onset latency would be prolonged in the dual-task compared to the

single-task. The N2pc parameters would be independent of the task situation, if general dual-task demands do not influence visual attention deployment.

7.2 Results and Discussion

The underadditive interaction of SOA and set size on RT2 was the most important behavioral result in the dual-task experiment. Comparing the set size effects (i.e., RT2 difference between the large and the small set size) between long SOA ($M = 143$ ms) and short SOA ($M = 82$ ms) revealed that the set size effect was significantly reduced at short SOA. Thus, again, visual search time was absorbed into the slack time. Moreover, there was an underadditive SOA and display type interaction. The RT2 difference between target absent and target present was significantly smaller at short SOA ($M = 58$ ms) compared to long SOA ($M = 90$ ms). Both interactions indicated that the visual attention processes in the conjunction search Task 2 (i.e., feature binding) operated concurrently to the response selection processes in the auditory two-choice discrimination Task 1.

Concerning the N2pc analysis in the dual-task, the amplitude was significantly reduced for the large set size compared to the small set size ($M = -1.36$ μ V vs. -2.06 μ V). The set size effect reflected that the N2pc was sensitive to the allocated amount of visual attention in the conditions of the conjunction search task. Most important for the research question, the amplitude was independent of SOA as shown in Figure 4. The mean amplitudes were -1.60 μ V, -1.74 μ V, and -1.78 μ V at SOAs 60, 400, and 800, respectively. Thus, the response selection processes in Task 1 did not affect the amount of visual attention that was allocated to the target. The peak latency was not modulated by SOA, but the amplitude peaked significantly later for the large set size ($M = 351$ ms) compared to the small set size ($M = 336$ ms). The findings revealed that the response selection processes in Task 1 did not delay target selection, however, the set size effect showed that the visual attention shift to the target was later for the large set size. There was no effect on the N2pc onset latency (see also Brisson & Jolicoeur, 2007a, 2007b; Lien et al., 2011). The response selection processes in Task 1 did not delay the onset of target selection in the conjunction search Task 2.

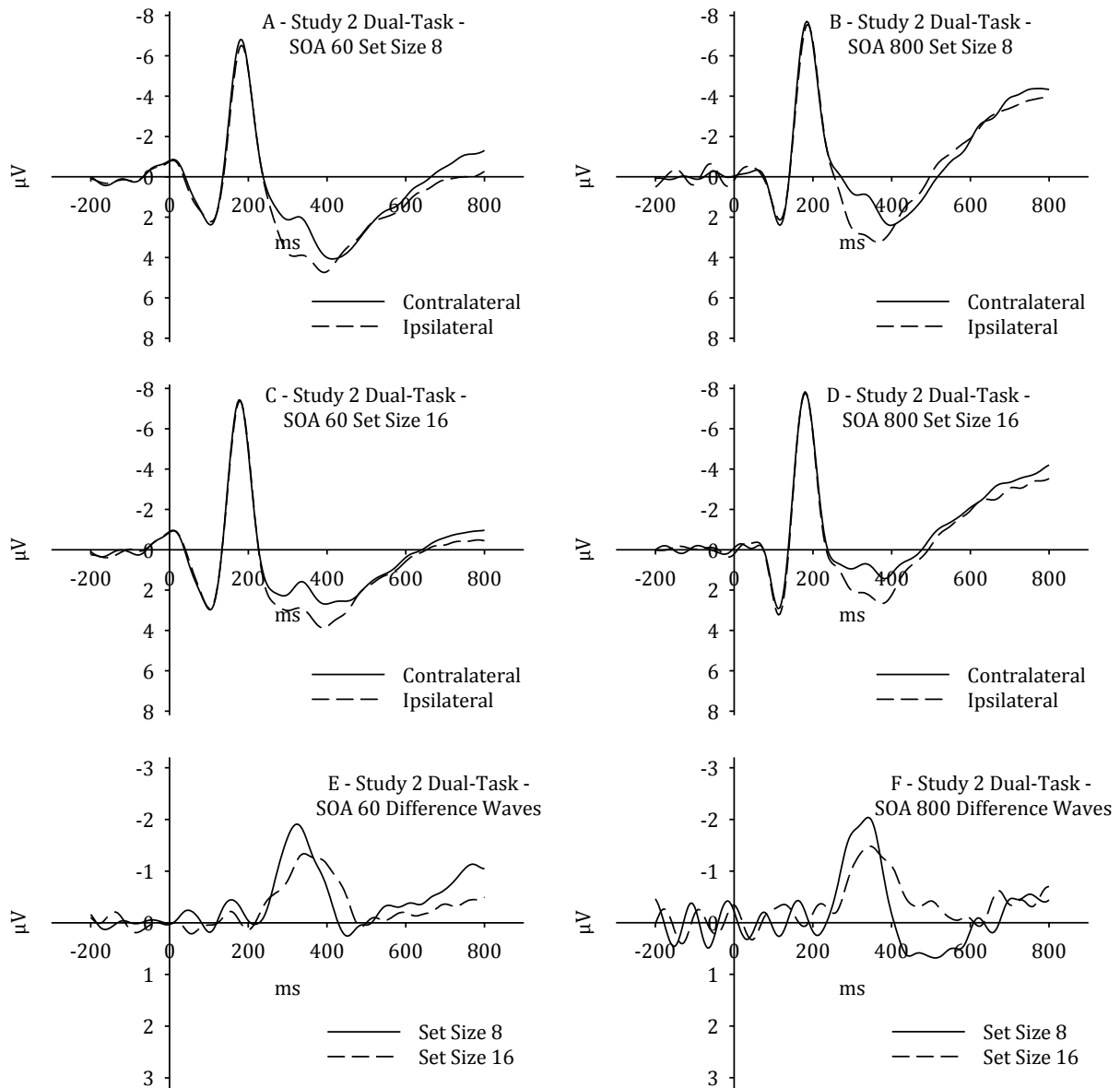


Fig. 4 Study 2, Dual-Task Experiment: A – D: Grand average ipsilateral and contralateral event-related potential waveforms at electrodes P07/P08 for set sizes 8 (A, B) and 16 (C, D) at Stimulus Onset Asynchronies (SOAs) 60 ms and 800 ms of the target present condition when conjunction search was performed as Task 2 in the dual-task. E – F: Grand-average N2pc difference waves (contralateral – ipsilateral waveforms) for set sizes 8 and 16 at SOAs 60 ms and 800 ms. Time 0 ms represents search display onset.

Concerning the N2pc analysis in the single-task, the set size effect on the amplitude was significant. The amplitude was reduced for the large set size ($M = -1.70 \mu V$) compared to the small set size ($M = -2.54 \mu V$). Correspondingly, the amplitude peaked significantly later for the large set size ($M = 386 \text{ ms}$) than for the small set size ($M = 338 \text{ ms}$). There was no effect on the onset latency. The findings stressed that the N2pc reflected visual attention processes, which were relevant for target selection in the conjunction search task.

Moreover, I compared conjunction search performance in the dual-task and in the single-task to assess the influence of general dual-task demands on visual attention deployment. For that purpose, the N2pc in the single-task was contrasted with the corresponding data at short SOA in the dual-task. The short SOA was chosen, because this condition represented the task situation where temporal overlap of Task 1 and Task 2 was maximal compared to the other two SOA conditions. Accordingly, the comparison between the N2pc in the single-task and at short SOA in the dual-task represented a comparison between the conditions that were least related with respect to cognitive processing (i.e., the condition of pure single-task processing vs. the condition of maximal dual-task processing). Therefore, this comparison was most informative to investigate the influence of general dual-task demands.

Concerning the results, the amplitude in the single-task ($M = -2.12 \mu V$) did not differ significantly from the amplitude at short SOA in the dual-task ($M = -1.60 \mu V$). However, the amplitude peaked later in the single-task ($M = 362 \text{ ms}$) than at short SOA in the dual-task ($M = 338 \text{ ms}$). Importantly, there were no statistical effects on the onset latency. Thus, general dual-task demands did neither substantially affect the amount of visual attention that was allocated to the target nor delay the onset of the visual attention shift. The peak latency effect should not obscure these findings. Rather, it seemed plausible to assume that in the single-task it took more time to reach a numerically higher peak compared to the short SOA in the dual-task.

To summarize the results of Study 2, the locus-of-slack method revealed that visual search time was absorbed into the slack time, indicating concurrent processing of response selection and visual attention. The N2pc analysis strengthened this finding. The amplitude and the onset latency were independent of SOA reflecting that the response selection processes did not affect visual attention deployment. Thus, the results

provided evidence for the assumption that visual attention (i.e., feature binding) and response selection rely on distinct capacity limitations. Furthermore, measuring the N2pc to compare visual attention deployment in the dual-task and in the single-task indicated that the amplitude and the onset latency were independent of the task situation. General dual-task demands did not affect the feature binding processes in the conjunction search task.

To discuss Study 2, in the dual-task experiment, the locus-of-slack method showed that visual search time was absorbed into the slack time. As in Study 1, it is of interest to calculate the absorbed search time and the corresponding number of items to quantify the amount of visual attention that is concurrently deployed to response selection. I will further discuss this topic in the General Discussion section (Chapter 9.2), where I will explain the method and the calculations to quantify visual attention processing. For the discussion of Study 2, it should be sufficient to say that 11.98 of 16 items were processed during the slack time when the target was present and 11.22 of 16 items when the target was absent. Put differently, almost three quarters of the items were processed during the slack time. Taken together, a large part of the visual attention processes operated concurrently to response selection, thus supporting the conclusion that response selection and visual attention rely on distinct capacity limitations.

Lien et al. (2011, Experiments 1 & 2) also concluded that response selection and visual attention operate concurrently. In their study, the N2pc was independent of SOA showing that response selection did not affect the initial visual attention shift to the masked search display. In Study 2, the search display was presented until response (i.e., non-masked). The N2pc was also independent of SOA, indicating that response selection did not impair visual attention deployment in a serial search process. The results of Study 2 thus extended the findings of Lien et al. (see also Pashler, 1989, 1991).

However, the results of Study 2 contradicted the results of Brisson and Jolicoeur (2007a, 2007b; see also Lien et al., 2011, Experiments 3 & 4). In their dual-task experiments, the N2pc amplitude was reduced at short SOA compared to long SOA. The authors concluded that response selection and visual attention interfere. They used an auditory four-choice discrimination Task 1, which is more difficult to perform than an auditory two-choice discrimination Task 1. It has to be investigated whether difficult

response selection processes impair visual attention (i.e., feature binding) in the conjunction search task. I will get back to this issue in Study 3 and in the General Discussion section.

The ERP technique allowed for comparing visual attention deployment in the dual-task (i.e., at short SOA) and in the single-task to reveal possible interference between visual attention and general dual-task demands. The results showed that the N2pc amplitude and the onset latency were independent of the task situation. Consequently, general dual-task demands did not affect the amount of visual attention that was deployed to the target nor delay the onset of target selection. However, the amplitude peaked later in the single-task compared to the shortest SOA in the dual-task. Because the amplitude was numerically larger in the single-task, it is possible that it took more time to peak. All in all, the results provided evidence that general dual-task demands did not affect the feature binding processes in the conjunction search task.

8 Study 3 ‘To mask, or not to mask, is not the question: Deploying visual attention to non-masked and masked search displays concurrently to response selection of another task’

Studies 1 and 2 investigated interference between response selection and visual attention deployment (i.e., feature binding) in a serial search process. The results of both studies provided evidence for the assumption that response selection and visual attention rely on distinct capacity limitations. The results were in line with the findings of Lien et al. (2011, Experiments 1 & 2) and Pashler (1989, 1991), but opposed the findings of Brisson and Jolicoeur (2007a, 2007b; see also Lien et al., Experiments 3 & 4). As described in the beginning, the authors often masked the search display. That is why it was important to investigate factors that seemed likely to impair concurrent performance of response selection and visual attention. As will be outlined next, two of

these factors were manipulated in Study 3: the response selection difficulty in Task 1 and the type of presentation of the search display in Task 2 (i.e., until response (non-masked) vs. masked).

8.1 Research question and Method

The aim of Study 3 was to disentangle the influence of the response selection difficulty in Task 1 and the influence of the mask in Task 2 on visual attention required for feature binding. Specifically, I addressed the question whether difficult compared to easy response selection processes in Task 1 impair (a) visual attention deployment in Task 2 in a serial search process (i.e., non-masked search display) and (b) target detection performance in Task 2 when the search display is masked, respectively.

In all dual-task experiments, Task 1 was an auditory choice discrimination task and the conjunction search Task 2 required target detection in displays of three set sizes (i.e., set sizes 6, 12, & 18; task adapted from Wolfe et al., 2010). The four SOAs between Task 1 and Task 2 varied between 50 ms and 800 ms. Visual attention deployment (i.e., feature binding) in Task 2 was investigated when the search display was presented until response (i.e., non-masked) (Experiments 1 & 2) compared to when the search display was masked after a brief exposure (Experiments 3 & 4). Both visual search conditions were presented with auditory two-choice and auditory four-choice discrimination Tasks 1, respectively, to examine the influence of the response selection difficulty in Task 1 on visual attention processing in Task 2. The participants were asked to respond as fast and as accurately as possible to both tasks with priority on Task 1.

In Experiments 1 and 2, the locus-of-slack method (Schweickert, 1978, 1980) was applied to test two hypotheses regarding sequential vs. concurrent processing of response selection and visual attention (i.e., feature binding) (Chapter 5.1, Figure 2). The hypotheses for the factors SOA and set size as well as for the factors SOA and display type were identical to the hypotheses in Study 1 (see Chapter 6.1). In Study 3, increasing the response selection difficulty in the auditory Task 1 from a two-choice (Experiment 1) to a four-choice (Experiment 2) discrimination could increase the possibility that the response selection processes affected visual attention deployment. In that case, the effect of set size would be additive with the effect of SOA. However, the slack time in Experiment 2 was expected to be longer than the slack time in Experiment 1 because

difficult response selection processes (i.e., four-choice discrimination) take more time. The locus-of-slack method predicts that if visual attention operates concurrently to difficult response selection, a larger part of the search time would be absorbed into the slack time in Experiment 2 compared to Experiment 1.

Before presenting the hypotheses regarding visual attention deployment when the search display was masked, the role of the mask should be described in more detail. Generally, masking the search display and focusing on accuracy measures provides another possibility to study visual attention deployment (Cameron, Tai, Eckstein, & Carrasco, 2004; Palmer & McLean, 1995; Wolfe, 2007). When the search display is presented briefly and followed by a mask, visual attention can only be deployed to the items during a critical period of time before the mask terminates any perceptual processing. In general, the brief exposure of the search display allows for one fixation during which visual attention must be deployed to the target. The chance that the first deployment hits the target depends on the signal strength of the target. More concretely, in a feature search task, the target signal is strong. Visual attention is likely to be deployed to the target during the first deployment while set size effects are negligible. In conjunction search, however, the target signal is weak. The possibility to find the target during the first deployment of visual attention is assumed to decrease with increasing set size and to result in a set size effect of target detection accuracy (Wolfe, 2007).

Experiments 3 and 4 were similar to Experiments 1 and 2, except that the search display was masked after a brief exposure. The exposure duration was individually determined in a staircase procedure and varied between 150 – 230 ms to preclude eye movements (Carpenter, 1988). In Experiments 3 and 4, d' was measured, an indicator of target detection performance (Green & Swets, 1966/1974). D' is calculated according to the formula $d' = z(\text{Hit}) - z(\text{False Alarms})$, where Hit is defined as the proportion of trials on which a target is present and correctly detected, False Alarms is defined as the proportion of trials on which a target is absent, but erroneously reported, and z is defined as the inverse function of the cumulative normal distribution. Increasing values of d' indicate better target detection. The hypotheses concerning d' were as follows: If response selection processing impairs visual attention deployment, d' would be decreased at short SOA compared to long SOA (Figure 2A), indicating that response selection and visual attention rely on a common capacity limitation. On the other hand, if

response selection processing does not impair the concurrent deployment of visual attention to the search display, d' would be similar at short SOA and at long SOA (Figure 2B). The finding would provide evidence that response selection and visual attention rely on distinct capacity limitations.

Increasing the response selection difficulty in the auditory Task 1 from a two-choice (Experiment 3) to a four-choice discrimination (Experiment 4) could increase the possibility that the response selection processes in Task 1 impair visual attention processing in Task 2.

8.2 Results and Discussion

In Experiment 1, the auditory Task 1 required an easy two-choice discrimination. The search display of the conjunction search Task 2 was presented until response (i.e., non-masked). The most important result was the underadditive interaction of SOA and set size. A planned comparison indicated that the set size effect (i.e., RT2 difference between the large and the small set size) was significantly reduced at short SOA ($M = 85$ ms) compared to long SOA ($M = 130$ ms). Thus, visual search time was absorbed into the slack time. The result provided evidence that response selection and visual attention operate concurrently, which replicated the main finding of Studies 1 and 2.

In Experiment 2, the auditory Task 1 consisted of a difficult four-choice discrimination. The conjunction search Task 2 was the same as in Experiment 1. Importantly, the interaction of the factors SOA and set size was once again significant. The planned comparison confirmed that the set size effect was significantly reduced at short SOA ($M = 48$ ms) compared to long SOA ($M = 141$ ms). Again, visual search time was absorbed into the slack time. The underadditive interaction revealed that the difficult response selection processes did not impair visual attention deployment in a serial search process.

To summarize the results of Experiments 1 and 2, both experiments provided evidence for the assumption that neither easy nor difficult response selection processes in Task 1 affected the feature binding processes in Task 2. Rather, the findings strongly suggested that response selection and visual attention rely on distinct capacity limitations.

To discuss Experiments 1 and 2, as predicted by the locus-of-slack method in case of concurrent performance, a larger part of the visual search time was absorbed into the slack time in Experiment 2 (i.e., difficult response selection in Task 1) compared to Experiment 1 (i.e., easy response selection in Task 1). The set size effect at short SOA was reduced from 85 ms in Experiment 1 to 48 ms in Experiment 2. More items were processed during the slack time in Experiment 2 compared to Experiment 1. The method that allows for calculating the number of items that are concurrently processed to response selection will be presented in the General Discussion section (Chapter 9.2). For the discussion of Study 3 it should be sufficient to say that 5.80 more items were processed during the longer slack time in Experiment 2 when the target was present (Experiment 1: 10.54 of 18 items, Experiment 2: 16.34 of 18 items) and 2.42 more items when the target was absent (Experiment 1: 9.83 of 18 items, Experiment 2: 12.25 of 18 items). Almost all of the items were processed during the longer slack time when the target was present and about two thirds of the items when the target was absent. Overall, the difficult response selection processes in Task 1 did not impair the feature binding processes in the conjunction search Task 2 when the search display was presented until response (i.e., non-masked). Thus, response selection and visual attention rely on distinct capacity limitations.

The results of Experiment 1 were again in line with parts of the findings of Lien et al. (2011, Experiments 1 & 2; see also Pashler, 1989, 1991) showing that easy response selection and visual attention operated concurrently. The results of Experiment 2, however, opposed parts of the findings of Lien et al. (Experiments 3 & 4) and the findings of Brisson and Jolicoeur (2007a, 2007b). Contrary to the authors, I found concurrent processing of difficult response selection and visual attention. Considering that the authors masked the search display, but I presented it until response (i.e., non-masked), it remained an open question whether difficult and easy response selection processes impair the visual attention shift to the masked conjunction search display. These questions were addressed in Experiments 3 and 4.

In Experiment 3, the auditory Task 1 required an easy two-choice discrimination and the display of the conjunction search Task 2 was masked. Most important, the d' analysis revealed that target detection performance was significantly better at short SOA

($M = 2.3$) compared to long SOA ($M = 2.1$) as shown in Figure 5. The finding indicated that the easy response selection processes did not affect visual attention deployment to the target at short SOA compared to long SOA.

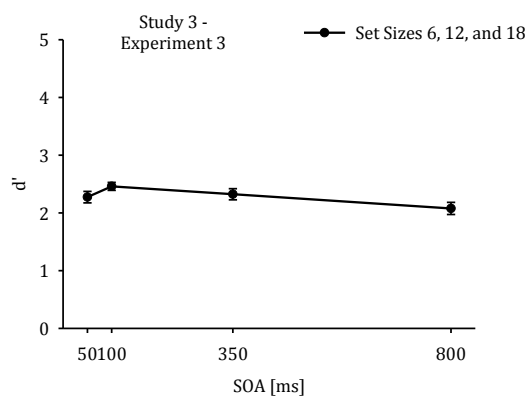


Fig. 5 Study 3, Experiment 3: Target detection performance d' of the masked conjunction search Task 2 depending on Stimulus Onset Asynchrony (SOA), here collapsed across set sizes 6, 12, and 18. Error bars represent standard error of the mean.

Experiment 4 was similar to Experiment 3, except that Task 1 required a difficult four-choice discrimination. The d' analysis showed that target detection performance was numerically still higher at short SOA ($M = 1.9$) compared to long SOA ($M = 1.8$), but the difference was not significant. Thus, difficult response selection in Task 1 did not impair visual attention deployment in Task 2 at short SOA compared to long SOA.

To summarize the results of Experiments 3 and 4, the d' analyses showed that neither easy nor difficult response selection processes in Task 1 impaired the visual attention shift to the masked search display in Task 2 at short SOA compared to long SOA. The results of both experiments indicated that response selection and visual attention rely on distinct capacity limitations. In Study 3 (Appendix C), distribution analyses were conducted in which d' was analyzed conditional on the speed of the Task 1 response. Although the analyses indicated an overall dependency between the speed of the Task 1 response and target detection performance in Task 2, they also showed again that response selection processing did not impair visual attention deployment at short SOA compared to long SOA.

To conclude, all experiments of Study 3 showed that in general the response selection difficulty in Task 1 (i.e., easy vs. difficult) and the type of presentation of the

search display in Task 2 (i.e., display presented until response (non-masked) vs. masked) did not lead to interference between response selection and visual attention.

To discuss Experiments 3 and 4, the response selection processes in Task 1 did not impair the initial visual attention shift in Task 2 at short SOA compared to long SOA. Even difficult response selection did not affect visual attention deployment at short SOA compared to long SOA when the search display was masked. Thus, response selection and visual attention rely on distinct capacity limitations. However, the findings that target detection performance was even better at the shorter SOAs, especially at SOA 100, than at long SOA were rather unexpected. It is possible that the participants made a greater effort at the shorter SOAs to deal with the more difficult dual-task conditions.

In Experiment 3, the results of the d' analysis were similar to parts of the findings of Lien et al. (2011, Experiments 1 & 2). The authors also found concurrent performance of easy response selection processes and visual attention shifts to the masked search display.

Concerning Experiment 4, the results of the d' analysis were in contrast to parts of the findings of Lien et al. (Experiments 3 & 4) and to the findings of Brisson and Jolicoeur (2007a, 2007b). In Experiment 4, target detection performance was not impaired at short SOA compared to long SOA, indicating concurrent processing of difficult response selection and visual attention deployment. The authors, however, showed evidence for interference between difficult response selection and visual attention deployment, as the N2pc amplitude was attenuated at short SOA compared to long SOA in their studies.

The diverging findings could be explained by the fact that the authors' search tasks (Brisson & Jolicoeur, 2007a, 2007b; Lien et al., 2011, Experiments 3 & 4) and the conjunction search task in Study 3 differed with respect to the visual attention demands. As outlined in the beginning, the authors used compound search tasks, respectively, which consisted of target-related and response-related visual attention processes. Since in their studies the target differed in color from the distractors, it is likely that it captured attention. The attention capture facilitated the visual attention shift to the target. That is why the target-related process did probably not interfere with difficult response selection. However, the response-related process required the discrimination

of the response relevant target feature. It is likely to assume that the discrimination processes resulted in interference with difficult response selection. To reconcile the authors' and my findings, it should be investigated whether difficult response selection and visual attention deployment interfere when the conjunction search task would not require target detection, but the discrimination of an additional target feature. In such a compound task that is shown in Figure 1C, an additional feature would be added to the conjunction stimuli, for example a vertical or horizontal midline. The task would still consist of feature binding processes to find the target, but also of discrimination processes regarding the orientation of the midline to give the correct response. Combining an auditory choice discrimination Task 1 with this compound task as Task 2 would provide a possibility to test whether interference between (difficult) response selection and visual attention is driven by the complexity of the visual attention processes.

9 General Discussion and Future Directions

After a short summary of Studies 1-3, the method to quantify visual attention deployment concurrently to response selection in dual-tasks will be presented. Implications and limitations of Studies 1-3 will be discussed along with future directions.

9.1 Summary of the present work

The present dissertation investigated whether visual attention required for feature binding is subject to the same bottleneck mechanism as response selection in dual-tasks. In all studies, the dual-task experiments consisted of a choice-discrimination Task 1 (i.e., manipulation of the response selection processes) and a conjunction search Task 2 (i.e., manipulation of the feature binding processes). Both tasks were presented with variable SOAs (i.e., manipulation of the temporal overlap). In all studies, the locus-of-slack method (Schweickert, 1978, 1980) was applied to test two hypotheses regarding sequential vs. concurrent processing of response selection and visual attention. In addition, in Study 2, the N2pc was measured, an ERP that indexes visuo-spatial attention

allocation (Eimer, 1996; Luck & Hillyard, 1994a, 1994b; Woodman & Luck, 1999, 2003). The N2pc was measured in order to examine whether response selection delays visual attention shifts and attenuates the amount of visual attention that is allocated to the target. In Study 3, d' that indicates target detection performance (Green & Swets, 1966/1974) was also measured.

Study 1 addressed the question whether response selection in Task 1 influences visual attention deployment in Task 2 in dual-tasks (a) in which the stimulus modalities differ across tasks (i.e., auditory Task 1, visual Task 2) and (b) in dual-tasks in which the stimulus modality is the same in both tasks (i.e., visual Task 1, visual Task 2). The results showed that irrespective of the stimulus modality in Task 1, response selection and visual attention operated concurrently. Even when the stimuli in both tasks drew on the same visual attentional capacity, performing the color discrimination in Task 1 did not impair the binding of color and form features in the conjunction search Task 2. The findings provided evidence that response selection and visual attention rely on distinct capacity limitations (see also Lien et al., 2011, Experiments 1 & 2; Pashler, 1989, 1991; but see Brisson & Jolicoeur, 2007a, 2007b; Lien et al., Experiments 3 & 4).

Study 2 investigated whether the N2pc analysis reveals the same or different results concerning visual attention deployment compared to the RT2 analysis based on the locus-of-slack method. Concerning the results, the N2pc was independent of SOA. The response selection processes in the auditory two-choice discrimination Task 1 neither delayed the onset of the visual attention shifts nor attenuated the amount of visual attention that was allocated to the target. The locus-of-slack method showed that visual search time was absorbed into the slack time. Thus, both analyses provided converging evidence for the assumption that response selection and visual attention rely on distinct capacity limitations (see also Lien et al., 2011, Experiments 1 & 2; Pashler, 1989, 1991; but see Brisson & Jolicoeur, 2007a, 2007b; Lien et al., Experiments 3 & 4).

Finally, Study 3 addressed the question whether difficult compared to easy response selection processes in Task 1 impair (a) visual attention deployment in Task 2 in a serial search process (i.e., non-masked search display) (Experiments 1 & 2) and (b) target detection performance in Task 2 when the search display is masked (Experiments 3 & 4), respectively. In Experiments 1 and 2, visual search time was absorbed into the slack time showing that response selection and visual attention operated concurrently.

Even the difficult response selection processes did not impair the feature binding processes in the conjunction search task (see also Lien et al., 2011, Experiments 1 & 2; Pashler, 1989, 1991; but see Brisson & Jolicoeur, 2007a, 2007b; Lien et al., Experiments 3 & 4). In Experiments 3 and 4, target detection performance was not impaired at short SOA compared to long SOA. Neither easy nor difficult response selection processes affected visual attention deployment to the masked search display. The findings of the d' analysis in Experiment 3 (i.e., easy response selection in Task 1) were in line with parts of the findings of Lien et al. (Experiments 1 & 2), but the findings of the d' analysis in Experiment 4 (i.e., difficult response selection in Task 1) were in contrast to the findings of Brisson and Jolicoeur and to parts of the findings of Lien et al. (Experiments 3 & 4). The authors found impaired visual attention deployment at short SOA compared to long SOA when Task 1 was difficult. It is possible that they found interference, because their compound tasks require different visual attention processes than the conjunction search task in Study 3. Taken together, the results of Study 3 showed that response selection and visual attention rely on distinct capacity limitations (see also Lien et al., Experiments 1 & 2; Pashler; but see Brisson & Jolicoeur; Lien et al., Experiments 3 & 4).

In conclusion, Studies 1-3 provided evidence that response selection and visual attention required for feature binding operate concurrently. Thus, both processes rely on distinct capacity limitations.

9.2 Quantifying visual attention processing in dual-tasks

As previously mentioned in the present dissertation, I developed a method to calculate the number of items in the visual search Task 2 that are processed during the slack time, which emerges from concurrently processing Task 1.

As displayed in Figure 6, visual attention deployment was separately quantified for the target present and the target absent condition in each study as follows. First, we consider the set size effects at long SOA and at short SOA. The set size effects represent the increase in search time from the small to the large set size condition. In the present dual-tasks, set size effects represent the part of the search time that is not absorbed into the slack time. In case the visual search time is fully absorbed into the slack time at short SOA, the set size effect would be absent. Subtracting the set size effect at short SOA from the set size effect at long SOA indicates the part of the search time that is absorbed into

the slack time. The absorbed search time corresponds to a certain number of items processed during the slack time. In order to calculate the number of items processed during the slack time, it is necessary to divide the absorbed search time by the search slope, the rate at which the items are processed. Likewise, in order to calculate the number of items processed after the slack time, it is necessary to divide the non-absorbed search time by the search slope. The search slope is calculated using linear regression. Here, the search slope is calculated at long SOA, because this SOA condition represents the visual attention condition that is least affected by Task 1 processing and is therefore most informative for visual attention deployment in dual-tasks. When dividing the absorbed search time by the search slope to calculate how many items are processed during the slack time, it is necessary to add the number of items of the small set size condition. The number of items of the small set size condition is added, because the locus-of-slack method implies that in case of absorption, the small set size condition is fully processed during the slack time and only the difference in processing time between the small and the large set size condition is measured. Finally, dividing the non-absorbed search time by the search slope reveals how many items are processed after the slack time. Adding the number of items that are processed during and after the slack time results in the number of items of the large set size condition. This approach is suited to review the calculations. The results of all studies are presented in Figure 6.

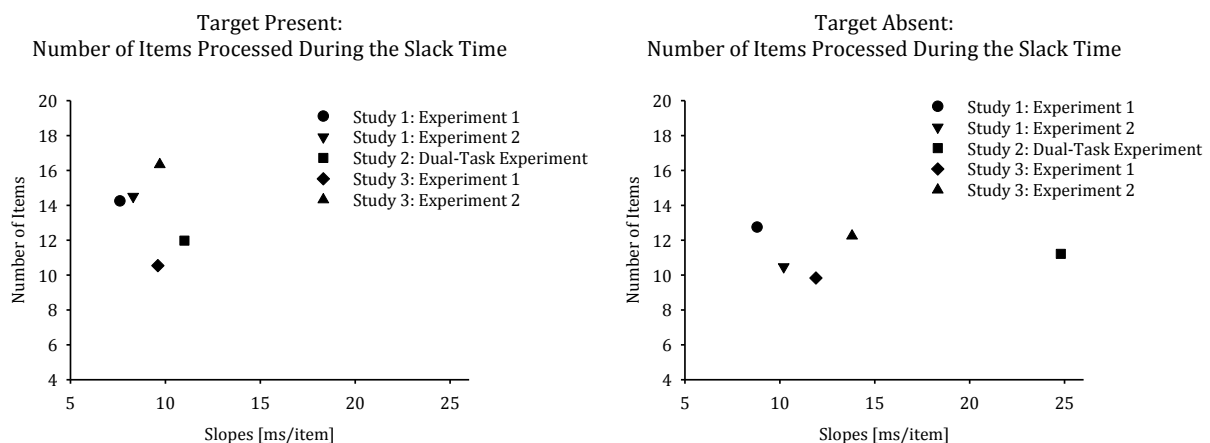


Fig. 6 Quantification of visual attention in dual-tasks: The graphs show the number of items that are processed during the slack time and the search slopes for the target present (left) and the target absent condition (right) in Studies 1-3.

In the present studies, the quantification method allowed me to compare visual attention deployment between different conditions. Most interesting is the comparison of visual attention deployment in Task 2 between easy and difficult response selection processes in Task 1 in Study 3. Figure 6 shows that when the target was present, the search slopes were similar for easy and difficult response selection processes (Experiment 1: 9.6 ms/item; Experiment 2: 9.7 ms/item). In other words, the difficult response selection processes did not slow the rate at which the items were processed. The slack time was longer when response selection was difficult (Experiment 2) compared to easy (Experiment 1), and 5.8 more items were processed during the longer slack time (Experiment 2: 16.34 items vs. Experiment 1: 10.54 items).

When the target was absent, 2.42 more items were processed during the longer slack time in Experiment 2 (12.25 items) compared to Experiment 1 (9.83 items). Interestingly, the difficult response selection processes slowed the rate at which the items were processed (Experiment 2: 13.80 ms/item vs. Experiment 1: 11.90 ms/item). Since the difficult response selection processes affected the search slopes only in target absent, but not in target present trials, they did not influence the feature binding processes per se, but rather processes that are specific for target absent trials. It is possible that the difficult response selection processes delayed the decision when to quit target absent trials. As explained in Chapter 3.1, in target absent trials, search often stops when a certain threshold is reached (Wolfe, 1994, 2007, 2012a). Here, when response selection was difficult, the participants may have searched longer than usual (i.e., time threshold) or among a larger subset of items than usual (i.e., activation threshold) before they decided to quit the search task.

The quantification of visual attention deployment in dual-tasks requires a set size manipulation. Since the other studies that investigated interference between response selection and visual attention did not use a set size manipulation (Brisson & Jolicoeur, 2007a, 2007b; Lien et al., 2011; Pashler, 1989, 1991), it is impossible to perform the calculations with their data and to compare the findings.

Furthermore, the question arises whether the quantification method could be adapted to other studies that applied the locus-of-slack method (for an overview of studies see Pashler, n.d.). Most of these studies manipulated the perception difficulty of the stimuli, for example the stimuli differed in contrast, were rotated or masked. In this

context, it is not possible to compute slopes that indicate the rate at which the stimuli (i.e., the contrasts) were processed. For these studies, it is in fact possible to calculate the absorbed processing time by subtracting the non-absorbed time at short SOA from the non-absorbed time at long SOA. However, without slopes it is impossible to quantify the processes that operated in parallel to response selection.

9.3 The visual attention processes in the search task are crucial for interference between response selection and visual attention

In Study 3, the response selection difficulty in Task 1 (i.e., easy vs. difficult) and the type of presentation of the search display (i.e., until response (non-masked) vs. masked) did not affect concurrent processing of response selection and visual attention. However, other studies found interference when Task 1 was difficult and the search display in Task 2 was masked (Brisson & Jolicoeur, 2007a, 2007b; Lien et al., 2011, Experiments 3 & 4). It is possible that Study 3 did not reveal interference, because the conjunction search task required different visual attention demands than the authors' tasks. The conjunction search task consisted of feature binding processes in a target detection task, but the authors examined attentional capture in compound tasks. More concrete, their tasks consisted of a target-related visual attention process and a response-related visual attention process. Since the target differed in color from the distractors, it was localized via attentional capture. The response consisted in discriminating the response relevant target feature. In Lien et al.'s study, the target letter had to be identified (i.e., two-choice discrimination) and in Brisson and Jolicoeur's studies, the stimuli were squares with a gap at one side and the location of the gap had to be identified (i.e., four-choice discrimination). It is likely to assume that in these tasks, the target localization was almost visual attention free, but the discrimination process required visual attention, as it consisted of binding the target features and identifying the response relevant feature.

In future studies, it should be investigated for the authors' tasks (Brisson & Jolicoeur, 2007a, 2007b; Lien et al., 2011) whether response selection and visual attention operate concurrently in case the compound aspect of the task is removed. In the new task, the stimuli would be the same, but a target present vs. absent decision could be required. Such a new task would be well-suited to examine whether response

selection affected attentional capture processes. In case response selection and attentional capture processes operate concurrently, it would be likely to assume that the particular response-related discrimination process, which is required in the search tasks of Brisson and Jolicoeur and Lien et al., may have caused the observed interference.

Moreover, in future studies, it should be investigated whether response selection and visual attention interfere if the conjunction search task does not require target detection, but the localization of the target and the discrimination of an additional target feature. In such a compound task that is shown in Figure 1C, an additional feature would be added to the conjunction stimuli, for example a vertical or horizontal midline. The task would still consist of feature binding processes to find the target, but also of discriminating the orientation of the midline to give the response. In addition, it could be considered to use a compound task that requires a four-choice discrimination like the task in the studies of Brisson and Jolicoeur (2007a, 2007b) in order to examine whether the response selection difficulty in the visual search task affects interference between response selection in Task 1 and visual attention in Task 2. However, Lien et al. (2011) found interference for a two-choice discrimination search task suggesting that the response selection difficulty in the search task does not influence interference.

Concerning the described future studies, it could be worthwhile to manipulate the response selection difficulty in Task 1 (i.e., easy vs. difficult), the stimulus modality in Task 1 (i.e., auditory vs. visual) and the type of presentation of the search display (i.e., until response (non-masked) vs. masked). Taken together, the future experiments would help to broaden the understanding of the role of the visual attention processes in the context of interference between response selection and visual attention.

9.4 Binding more than two features to test the limits of visual attention deployment during the slack time

In Studies 1-3, the conjunction search tasks required the binding of color and form features. Overall, response selection did not impair the binding of two features per item. However, in future studies, it should be investigated whether response selection impairs the binding of more than two features, for example four features. Binding four features per item is assumed to require more visual attention than binding two features

(Wolfe, 1994, 2007). In that case, it is possible that visual attention cannot operate concurrently to response selection anymore.

Based on this reasoning, I conducted a dual-task experiment (unpublished data) that consisted of an auditory two-choice discrimination Task 1 and a new conjunction search Task 2. In this new search task, the stimuli were crosses and each cross was composed of four features (Wolfe, 2012b; Wolfe & Bennett, 1997). The target cross consisted of a red vertical and a green horizontal bar. The distractor crosses consisted of a green vertical and a red horizontal bar, respectively. In this task, visual attention was heavily required to select the items in a serial search process in order to bind the features. The results suggested that response selection and visual attention operated sequentially, as visual search time was not absorbed into the slack time. To conclude, when the feature binding demands exceed a certain level (i.e., binding four features instead of two features), visual attention cannot be deployed concurrently to response selection anymore. Thus, the experiment provided preliminary evidence that the visual attention demands are crucial in the context of interference between response selection and visual attention.

9.5 Measuring ERPs in a target detection task

In Study 2, the N2pc was measured to investigate interference between response selection and visual attention. The N2pc indexes lateralized visuo-spatial attention deployment, in particular the selection of the target in a visual search task (Eimer, 1996; Luck & Hillyard, 1994a, 1994b; Woodman & Luck, 1999, 2003). The N2pc is more negative at electrodes contralateral to the side of the attended stimulus (i.e., target) compared to ipsilateral. It follows that the N2pc is exclusively computed for target present trials. For target absent trials, however, it could be of interest to measure a component of the lateralized readiness potential (LRP). Measuring an ERP in both target present and target absent trials could reveal more about the mechanisms of visual attention deployment in target detection tasks.

More concretely, the LRP indexes response activation and preparation at the motor cortex level and is strongest over motor areas that are contralateral to a unilateral hand/foot movement (Coles, 1989; Hackley & Valle-Inclan, 2003; Miller & Hackley, 1992). In the context of interference between response selection and visual attention,

the stimulus-locked LRP (s-LRP), which is a specific component of the LRP, could be of particular interest for target absent trials. When locking the s-LRP to the onset of the search display, it would be possible to measure response activation processes before the response is produced. In future studies, the s-LRP amplitude and onset latency could be measured to reveal more about the influence of response selection in Task 1 on the time point when target absent trials in Task 2 are quit (Wolfe, 1994, 2007, 2012b; Chapter 9.2).

9.6 Concurrent performance of response selection and visual attention from the central capacity sharing perspective

In Studies 1-3, the working model for response selection processing in dual-tasks was the central bottleneck model (Pashler, 1994; Schubert, 1999, 2008; Welford, 1952). As mentioned in the beginning, capacity sharing models are an alternative to the central bottleneck model (Kahneman, 1973; McLeod, 1977; Navon & Gopher, 1979; Navon & Miller, 2002; Tombu & Jolicoeur, 2003, 2005). The central capacity sharing model (Tombu & Jolicoeur) should be considered in more detail. This model can account for underadditive patterns that can occur when a processing stage earlier than response selection is manipulated in Task 2. It is therefore of interest to examine if the model can account for the findings of Studies 1-3.

According to the central capacity sharing model (Tombu & Jolicoeur, 2003, 2005), central processing stages like response selection are limited in capacity. The model assumes that the central stages can process multiple stimuli at the same time. Whenever the response selection stages in Task 1 and Task 2 of a dual-task are processed in parallel (i.e., as is typical at short SOA), processing capacity is shared and the processing in both tasks slows down.

The central capacity sharing model (Tombu & Jolicoeur, 2003, 2005) can account for underadditive patterns on RT2. For the dual-tasks in Studies 1-3 (i.e., choice discrimination Task 1 and conjunction search Task 2), the model would explain underadditivity as follows. Considering that in the conjunction search Task 2, processing the small set size takes less time than processing the large set size. At short SOA, the corresponding response selection processes would start right after the stimuli (i.e., small and large set size) would have been processed. In both conditions, processing capacity

would be shared between the response selection in Task 2 and the response selection in Task 1. Processing capacity would be shared for a longer period of time for the small set size than for the large set size, because sharing processing capacity slows down the processing both in Task 1 and in Task 2. That is, the increase in search time from the small to the large set size would be compensated by a decrease in response selection time from the small to the large set size. Overall, at short SOA, RT2 would be similar for the small and the large set size. Importantly, at short SOA, the set size manipulation in Task 2 would also affect RT1. Since sharing processing capacity between Task 1 and Task 2 would slow down the processing in both tasks, response selection in Task 1 would take longer when the small set size would be processed in Task 2 compared to the large set size. In turn, RT1 would increase for the small set size compared to the large set size. At long SOA, Task 2 would start after Task 1 would have been finished. The increase in search time from the small to the large set size would be added to RT2, but the set size manipulation would not affect RT1.

Taken together, for Studies 1-3, the central capacity sharing model (Tombu & Jolicoeur, 2003, 2005) would predict an underadditive interaction of SOA and set size on RT2 (i.e., no set size effect at short SOA, but a set size effect at long SOA) along with an interaction of SOA and set size on RT1 (i.e., set size effect at short SOA, but not at long SOA). In the experiments presented in this dissertation in which the locus-of-slack method was applied showed an interaction of SOA and set size on RT2, but not on RT1. Therefore the results cannot be explained in terms of the central capacity sharing model (Tombu & Jolicoeur).

9.7 Conclusion

To conclude, the present dissertation investigated whether visual attention required for feature binding is subject to the same bottleneck mechanism as response selection in dual-tasks. The behavioral results based on the locus-of-slack method and on d' as well as the electrophysiological results of the N2pc showed that response selection and visual attention operated in parallel. Visual attention was concurrently deployed to auditory (Studies 1 & 2) and visual two-choice discrimination tasks (Study 1) as well as to auditory two- and four-choice discrimination tasks both when the search display was presented until response (i.e., non-masked) and masked (Study 3). In each

study, visual attention deployment was quantified according to a method that has been developed in the present dissertation in order to reveal how many items were processed in parallel to response selection. Depending on the dual-task, between 54 % and 90 % of the items were actually processed in parallel to response selection. Overall, the results indicated that response selection and visual attention (i.e., feature binding) rely on distinct capacity limitations. Thus, the architecture of the cognitive system allows for selecting relevant visual information while performing another task, which is relevant considering the multi-tasking demands in everyday life. However, the limit of concurrent performance should be tested in future studies by investigating whether response selection impairs visual attention deployment in compound tasks and the binding of more than two features.

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Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt,

1. dass ich die vorliegende Arbeit selbstständig und ohne unerlaubte Hilfe verfasst habe,
2. dass ich mich nicht anderwärts um einen Doktorgrad beworben habe und noch keinen Doktorgrad der Psychologie besitze,
3. dass mir die zugrunde liegende Promotionsordnung der Mathematisch-Naturwissenschaftlichen Fakultät II vom 17.01.2005, zuletzt geändert am 03.08.2006, veröffentlicht im Amtlichen Mitteilungsblatt der Humboldt-Universität zu Berlin, Nr. 34/2006, bekannt ist.

Berlin, den 15. Juli 2016

Christina B. Reimer